GEOLOGY AND GEOCHEMISTRY OF BASE METAL DEPOSITS AROUND DARJEELING HIMALAYAS

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This is to certify that Mr. Hasan Mohammad has completed his research work under my supervision for the degree of Doctor of Philosophy of the Aligarh Muslim University. This work is an original contribution to the existing knowledge of the subject.

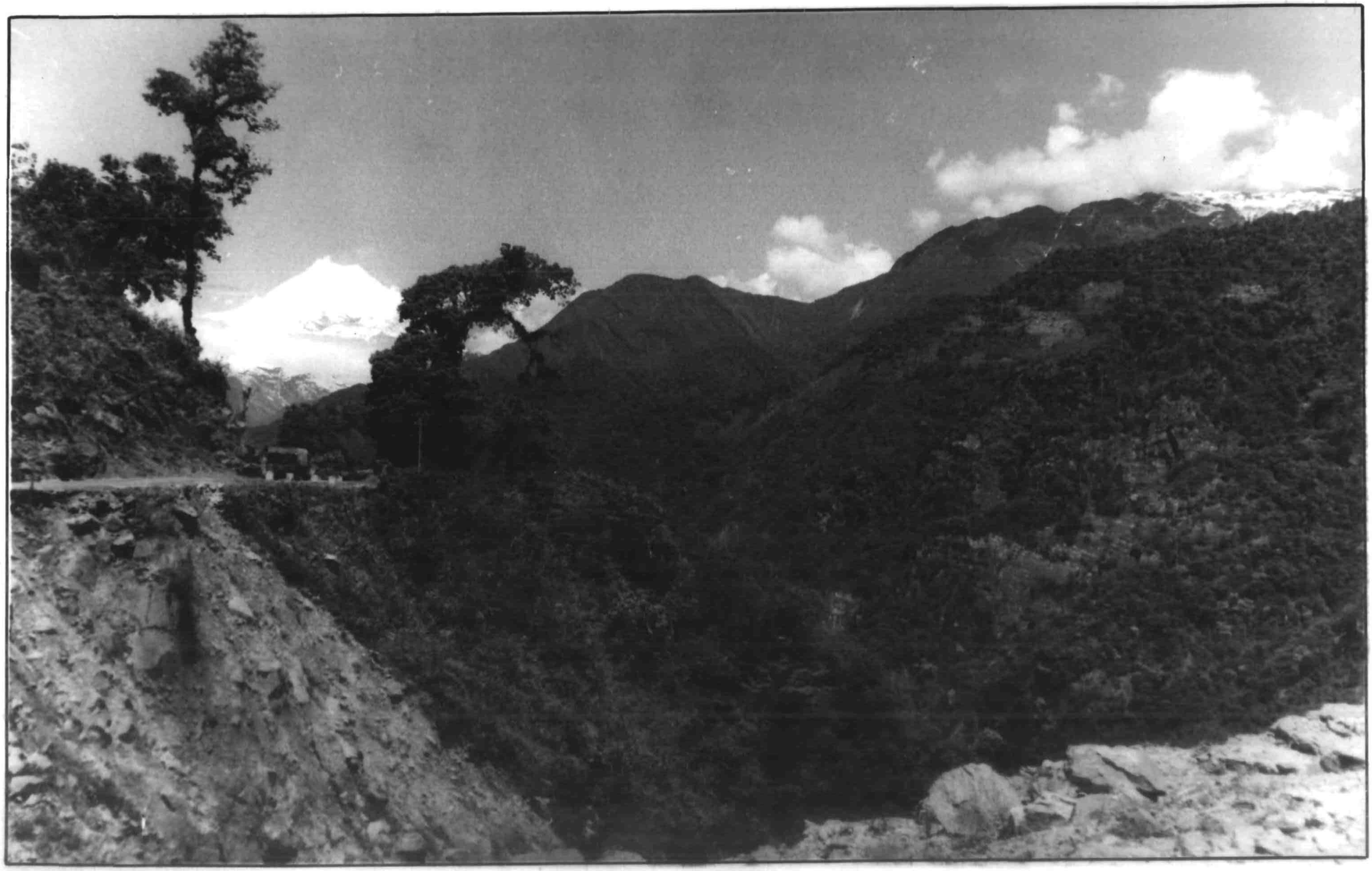
He is allowed to submit the work for the Ph.D. degree of the Aligarh Muslim University, Aligarh.

S. H. Rasul

February, 1973

S.H. RASUL
Supervisor

A TOPOGRAPHIC EXPRESSION OF DARJEELING GNEISS
AND DALING SERIES IN THE TISTA VALLEY
DARJEELING HIMALAYAS



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Chapter-I

INTRODUCTION

Location and accessibility

The work area lies between North latitudes 26°45' and 27°20' and East Longitudes 87°00' and 88°45' and included in parts of Survey of India toposheet No. 78A. The area is about 30 km away from Siliguri, the nearest Railway junction on the North Eastern Frontier Railway in West Bengal, and approachable by National Highway 31A. A few all weather roads, which are newly constructed, greatly facilitated movement in the area almost throughout the year. A major part of the area was, however, approachable through the briddle paths and foot tracks. The important towns in Darjeeling district, West Bengal, and Sikkim, all within a distance of 80 km are Darjeeling, Kalimpong, Singtam, Namchi, Nayabazar and Gezing. Darjeeling is the headquarter of Darjeeling district, West Bengal (Fig. 10).

Climate

The Eastern Himalayas experience severe monsoon with an average annual rainfall of 200 inches. Even the so-called dry seasons have excessive rainfalls. This is the reason of luxuriant growth of vegetation on the slopes of this part of Himalayas and as a result of which many geological features have been obscured. The winter months are

severely cold and chilly.

Physiography

The area around Darjeeling Himalayas forms a part of Lesser and Sub-Himalayan ranges and exhibits a typical mountainous topography with deep valleys and steep scarp faces. The average elevation of the valley floors in the area varies from 320 meters to 457 meters above m.s.l. whereas on the east, west and north, the higher peaks have different altitudes, the highest one being 1,525 meters above m.s.l. The relief of the area is, therefore, very great.

The southerly flowing Ranjit and Tista rivers (Figs. 1 & 2) with their tributaries form the principal drainage of the work area. Within the study area on the east, the Ranjit river joins the Tista river which is also another important part of the drainage system of this part of Eastern Himalayas. The confluence of these two rivers is at Melli, nearly 3 km south of Tista village. The area has also numerous other smaller tributaries which are locally termed as nalla, chu, khola or nadi. Fed by heavy snow and ice at higher altitudes on the north and heavy rainfall over the southern slopes of the Himalayas, these main rivers have carved out the deep and narrow valleys in an almost north-south direction. The general pattern of drainage in the area is dendritic. On the western side of Ranjit valley is the famous Singalilla ridge on which stands the famous Kanchenjunga peak (8,590 m). The Darjeeling hill ranges on the south and southeast of Kanchenjunga also form a part of the Singalilla ridge.

Previous work

Due to climatic reasons as well as many other prohibitive factors, this part of Himalayas was practically neglected and remained a terra incognita. Very few workers have so far entered the terrain, and most of their field study remained restricted to the foothill regions. Gansser (1964) has rightly pointed out that "The more one moves eastwards along the Himalayan chain, the more difficult it becomes to undertake geological investigations".

Geological investigations in Sikkim and in the adjoining region in Bengal began in the middle of the last century. Hooker (1854) reported in his famous Himalayan Journals an account of his extensive tours lasting for about two years in different parts of Sikkim. Later investigations by Hallet (1875) in the Darjeeling district and its foothills provided some preliminary informations regarding the stratigraphy and structure of the area. Bose (1891) in his excellent geological account of Sikkim also referred to her mineral resources. He (1891) also prepared the first geological map of Sikkim. Occurrences of sulphide ores in this part of the Himalayas were first reported by Hallet (1875) and latter by Bose (1891) but both of them described only the physical characters of the ores. A very brief account of the geology of some parts of Sikkim was given by Garwood (1903). Hayden (1907) has described the geology of only a few sections in northeastern Sikkim. A few sections in Northern Sikkim were also described by Van Loczy (1907), Dyhrenfurth (1931) and Wager (1934, 1939). The study of regional stratigraphy and structure of Darjeeling Himalayas and Sikkim was the main concern of Ray (1947), Auden (1935) and Ghosh (1952). Heim and

Gansser (1939) had taken several traverses to Gangtok (Sikkim) and the adjoining region of Darjeeling district. Some informations on the regional stratigraphy of Sikkim were compiled by Gansser (1964). Das Gupta (1968) has given some recent informations regarding the geology of the area around Darjeeling Himalayas.

Nothing could be known about the investigations that have recently been carried by the Geological Survey of India in the region because the reports are still lying unpublished.

Purpose of work

Keeping in view the limitations of previous work and certain problems of the base metal deposits in the Darjeeling Himalayas, the present investigation has been planned. An attempt has been made by the present author not only to study the structure, stratigraphy, etc. of the area, but also to make a detailed investigation of the sulphide mineral occurrences and the rocks associated with them particularly, with respect to their geochemistry, mineralogy, and the probable nature and source of mineralization. The author has also devoted much time to prepare the geological maps of the area and also of some of the individual mineral deposits.

Methods and presentation of work

Investigations were carried out broadly on the following lines:

I. Field investigations

During the course of field investigations, which extended over a period of about 3 years stay in the study area, geological maps of the

area and of the ore deposits were prepared. Necessary help of aerial photographs was taken, as and when required. The nature of the work, carried out, is given below:

A. Geological mapping

An area of about 140 sq. km was mapped on a scale 2 cm = 1 km, and an area of about 400 sq. miles was mapped on a scale 1 inch = 1 mile.

B. Detailed mapping around mineralized zones

Detailed mapping of about 8 sq km of the areas around the copper, lead and zinc deposits was done using plane table on scales of 1:2,000, 1:1,000 and 1:200.

C. Collection of samples for analytical work

Relevant samples of rocks, minerals and ores were carefully collected for the petrographic, mineragraphic, spectro-chemical, neutron activation analysis, etc. The samples included the varieties of grab, groove and the channel types from the mineralized as well as barren zones.

II. Laboratory investigations

Petrographic and mineragraphic studies

The study of rock and ore samples was done in the transmitted and reflected light respectively.

X'-ray analysis

X'-ray differactometry for the specific identification of some of the minerals has been done.

Chemical analysis

Systematic analysis of samples for the determination of the major elements was done by the conventional chemical methods.

Spectrographic analysis

Abundance of trace metals like Cu, Pb, Zn, Ni, Co, Cr, etc. in various samples have been quantitatively determined by emission spectrography. Hilger automatic large quartz and glass spectrograph was used. Trace element analyses of some of the samples were also done by Atomic Absorption Spectrophotometer.

Isotopic analysis

Some rock and mineral samples were analyzed for determining the isotopic ratios of sulphur, lead, oxygen and carbon.

Neutron activation analysis

Neutron activation analysis of the ore samples was done for the quantitative determination of their metal contents. The samples were irradiated for a specific period at various neutron fluxes. The measurement of the gamma radiation emitted by the activated elements from the samples and standards involved the use of a 4" x 4" well-type Na I(Tl) scitillation detector coupled to a 400 channel pulse height analyzer. The photo peaks in the gamma-ray spectrum, produced were counted.

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Chapter II

STRATIGRAPHY AND LITHOLOGY

I. Regional geology and stratigraphic setting

The regional geology and stratigraphic setting in this eastern part of the Himalayas have been briefly discussed, as it may be helpful to understand the geology of the work area. According to Gansser (1964) the physiographic divisions of the Himalayas are as follows:

1. Sub Himalayas
2. Lower Himalayas
3. Higher Himalayas
4. Tibetan Himalayas

The following tectonic zones of the Himalayas from northeast to southwest have been suggested by Ghosh (1956) and others:

Tethys Himalaya		Tibetan Zone
Great Himalayas	Root Zone	Permocarboniferous sediments underlain by metamorphic rocks.
Sub-Himalayas	Para-autochthon	Gneisses and Granites Baxa series, Daling series, and Darjeeling Gneiss ---?--Thrust---?--- Gondwanas
	Autochthon	Tertiary Belt ---?---Foothill Fault---?--- Duars Trough ----Hinge belt(?)----------
Gangetic plains		Foreland

Instead of giving unnecessarily details regarding the stratigraphy of the entire region, an idea of more salient features of regional importance is presented hereunder.

The Himalayas form the southernmost high ranges in Asia, and border the southern part of Tibetan Plateau and the Pamir mass. The two ends of Himalayas in the West and East form spectacular syntaxial bends (Fig. 11). The Himalayas are thrust against the Indian Shield or rather underthrust by the latter. The rocks belonging to the shield areas of Peninsular India with a Precambrian structural and lithological background occurring in parts of Lower Himalaya played an important role in the tectonic set-up. The original composition and structural fabric of these rocks have not always been maintained, but they have been altered or superimposed during their involvement in the tectonic disturbances from Upper Cretaceous to Recent.

The tertiary formations form an almost continuous fringe along the foothills (Sub Himalayan Zone). This is the southern limit of Himalayan ranges towards the foreland -- the Peninsular Shield. The tertiary Siwalik deposits are essentially fluviatile and consist of arkosic sandstones, siltstones, conglomerates and pebble beds. The highly folded rocks of this Sub Himalayan Zone are 'autochthonous'.

The northern edge of the Siwalik Mollasse is clearly outlined by a steep north dipping thrust plane, known as the 'Main Boundary Fault' (Fig. 1). It is along this fault zone that the Siwaliks have been overridden by the older rocks (Lower Himalayan Zone) such

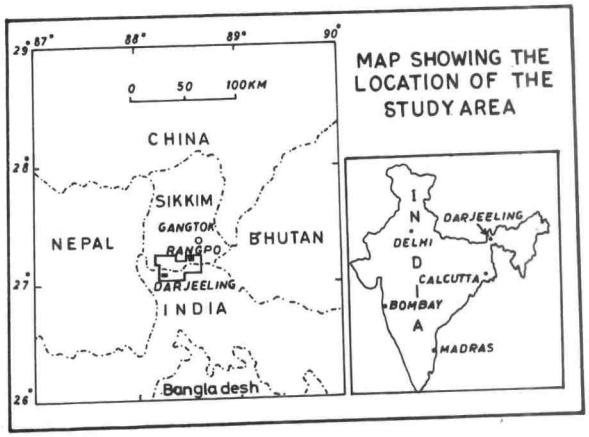
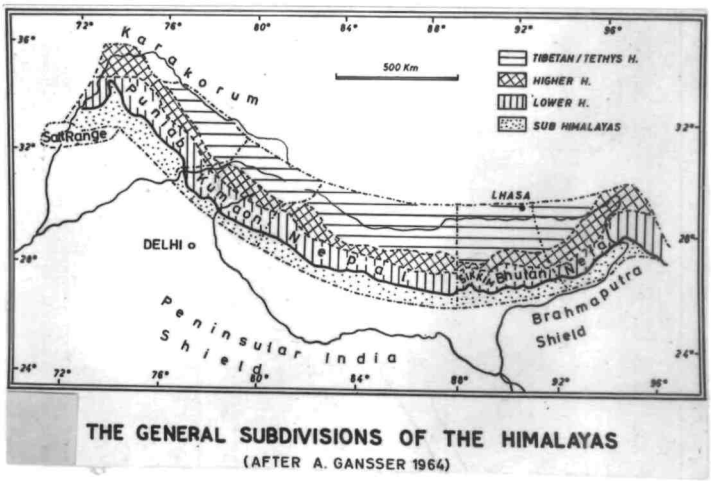


Fig. 10



THE GENERAL SUBDIVISIONS OF THE HIMALAYAS
(AFTER A. GANSSER 1964)

Fig. 11

the
as/Upper Mesozoic rocks of Gondwanas (Sandstones, shales, coal seams, etc.) and the Precambrian rocks of Baxas (dolomites, dolomitic limestones, slates, etc.), rocks of the Dalings (phyllites, slates, etc.), and the highly metamorphosed gneisses of Darjeeling Gneiss Group.

A greater proportion of rocks composing the Lesser or Lower Himalayan Zone belong to the border facies of Peninsular Shield. Effects of tectonic activity of a severe nature may be observed all along the 'Main Boundary Fault' in this part of eastern Himalayas. Independent tectonic sheets like Baxas have also been brought within this tectonic zone. In a south to north cross-section of the Lower Himalayan region of Sikkim and Darjeeling district the older thrust sheets follow successively. This is well documented by the thrust of the older Daling sheet over the Baxas.

The lithology and structure of these thrusted masses in the inner regions of Lower Himalayas show considerable regional variations. As a general rule, in this part of the Lesser Himalayas the high grade metamorphic rocks overlie less metamorphosed ones. It has a great bearing on the major structure of the area. The Gondwanas, Daling and Darjeeling series form a huge recumbent fold, which continues up to the great Kanchenjunga massif with its fold axis oriented in an east-west direction. The upper limb of the fold has been largely eroded forms the 'para-autochthonous zone'.

The rocks belonging to the less metamorphosed Lower Himalayan
and
group/form the base of the crystalline rocks of Higher Himalayas.

The crystalline rocks of the Higher Sikkim Himalayas include mainly gneisses and schists with slates, phyllites, quartzites and calc-granulites of Precambrian age. They have been intruded by the younger tourmaline granite of tertiary age. While the Western Higher Himalayas have a striking and distinguishing junction with the Lower Himalayas, but the picture in Sikkim is not so simple. A clear division between the Lower and Higher Himalayas was somewhat arbitrarily traced. Within the crystalline rocks of Sikkim Himalayas the grade of regional metamorphism generally decreases upwards. Above the Main Thrust Sheet, where the metamorphism is of lower grade, lie the younger mesozoic sediments of Everest type (Tibetan Himalayas).

The general stratigraphic sequence of the Darjeeling and Sikkim Himalayas, as compiled by Karunakaran (1964), is given in table 1.

II. Stratigraphy and lithology of the area

General statement

The investigations, carried out by the author, were mostly confined to the Lower Himalayan Subdivision of the Darjeeling Himalayas. The almost complete absence of fossils in the Lower Himalayas on the other hand leaves many stratigraphic problems unsolved. It is with these difficulties in mind that the geology of this part of Lower Himalayas has been studied. In spite of many regional and some detailed investigations of the Indian stratigraphy, which began with the foundation of Geological Survey of India over 120 years ago, our knowledge of the stratigraphy of this part of the Himalayas is still incomplete. An attempt has been made to describe the lithology and

TABLE - 1 Stratigraphic sequence around Darjeeling Himalayas.

Standard Time-scale	Rock formations	Zones of regional metamorphism	Indian stratigraphic horizons
Pliocene-Middle Miocene	Arkosic sandstones containing lignite, micaceous sandstones, conglomerates, pebble beds and blue and green siltstones.	----------	Siwalik System
---------- Thrust Plane (Main Boundary Fault) ----------			
Permo-Carboniferous	Fine to medium grained quartzitic sandstones interbedded with thin slate beds, carbonaceous shales and thin seams of flaky coal. Pebble and conglomerate beds at and near the base.	----------	Lower Gondwana System
---------- Tectonic Contact ----------			
	Dolomites, marl and slate; Pegmatites and quartz veins; slate, phyllite, quartzite, graywacke and epidiorites.	Chlorite and biotite zone	Baxa Series Daling Series
Pre-Cambrian	Golden and silvery mica-schists, meta graywackes, quartzite, amphibolite, para-and ortho-gneiss, graphitic schist, calc-gneiss and amphibolite.	Garnet and Staurolite Zones; Kyanite and Sillimanite Zones.	Darjeeling Series

distribution of various rock types of the area under discussion. The chief lithologic units are crystalline dolomitic limestones, some altered carbonate rocks, metamorphosed quartzites, shales, sandstones, schists, phyllites, gneisses, etc. Lamprophyres and basic rocks occur as sills. The structure has played an important role in the control and disposition of the various lithological units. The rocks of the area were subjected to intense deformation and dislocation during the tertiary period, and due to which the tectonic set-up of the area become complicated.

Stratigraphic sequence

The following stratigraphic sequence has been recognised in the area :

Alluvium	Sand and gravel	Recent to Subrecent
Older alluvium	High level terraces of sands and gravels	
Siwalik System	Sandstones, mudstones, clays, shales and pebble beds with thin bands of limestones and lignites	Miocene
- - - - - - - - - - - - - - - - Thrust - - - - - - - - - - - - - - - -		
Post-Gondwana intrusions	Lamprophyres, basic and ultra basic sills and dykes	Jurassic
Damuda Series (Gondwanas)	Sandstones, Carbonaceous shales, slates, pebble and boulder beds, and thin coal seams	Permian
- - - - - - - - - - - - - - - - Thrust - - - - - - - - - - - - - - - -		
Baxas	Dolomites, limestones, dolomitic limestones, phyllites and quartzites	Cambrian (?)
- - - - - - - - - - - - - - - - Tectonic contact (?) - - - - - - - -		
Daling Series and Darjeeling Series	Phyllites, slates and schists with minor bands of quartzites, Granite-gneisses, etc.	Pre-Cambrian

In course of the present investigation several observations have been made which might question the validity of the age relation of the dolomitic rocks viz-a-viz the Daling and the Gondwanas as tabulated above. This will be discussed later while describing the Baxa Series. Similarly, the age relation of Daling and Darjeeling Series, which has been a subject of great controversy in the Indian stratigraphy, has also been dealt briefly while discussing the Daling Series. The correlation of the stratigraphic succession of the area with similar other formations in other parts of the Himalayas has already been made by the previous workers (Wadia, 1957; Gansser, 1964).

Darjeeling and Daling Series

General statement

The stratigraphic relation between the more metamorphosed Darjeeling Series and the less metamorphosed Daling Series is still a debatable topic in Indian stratigraphy. Mallet (1875) considered the Darjeeling gneiss as younger to the Dalings. According to Bose (1891) the Darjeeling gneisses are older than the Dalings. Dyhrenfurth (1931) and Wager (1939) believed that the Darjeeling gneiss was underlain by the Daling Series and that these two groups of rocks are separated by a thrust plane. Wager (1939) thought that the intrusion of granites into the Dalings had caused the Dalings to resemble Darjeeling gneisses, and remarked that, "this may one day afford a clue to the origin of the latter". Auden (1935) was of the

opinion that the terms Daling and Darjeeling gneiss might apply respectively to the upper and lower portions of a great sedimentary succession, the lower part of which had been injected and metamorphosed by granite magma. He (1935) also considered that the two rock groups belong to different metamorphic facies rather than definite stratigraphic units and separated from each other by a thrust plane. According to Ray (1947) the stratigraphic sequence of the two series of the rocks is continuous and the (?) thrust plane does not mark a stratigraphic boundary. He (1947) also advocated for retaining the names - Daling Series and Darjeeling Series - in their original sense so that they may be distinguished by their individual metamorphic and lithologic characters. He also suggested that, at least, from stratigraphic viewpoint, the entire sedimentary sequence, consisting of Daling Series and Darjeeling Series, be treated as one formation and named "Senchal Series" (adopted after the name of the highest peak in these hills).

Majority of the previous workers are of the opinion that the Daling Series passes imperceptibly upwards into the overlying gneisses of the Darjeeling Series in the Sikkim and Darjeeling Himalayas. According to Pascoe (1964) there is a good reason to believe that the so-called Darjeeling gneiss is a crystalline complex comprising both meta- igneous and/sedimentary rocks, the former consisting chiefly of varieties of biotite gneiss, and the latter principally of quartzites, limestones and marbles, calciphyres and calc-granulites, mica-quartz schists, hornblende schists and a Daling-like clay-slate. In the area

under investigation, the 'crystalline complex' of Darjeeling series is represented only by 'granite-gneisses'. Some xenoliths of quartzites and marbles in the granite-gneisses have been found to occur at a few places in the area and at many places outside the Darjeeling Himalayas. For example, north-east of Darjeeling and at Tonglu, large rounded pieces of quartzites occur in the gneiss. Such xenoliths of calcareous and quartzitic rocks are generally well exposed in the northern areas.

Recently Mukhopadhyay and Gangopadhyay (1971) superposed the Daling-Darjeeling boundary on Mallet's (1874) geological map and retained the terms 'Darjeeling and Daling' as used by Mallet to indicate the state of metamorphism. They (1971) also failed to observe any thrust along the Daling-Darjeeling contact and found that the low grade metamorphic rocks gradually passed into higher grade rocks across the boundary. The boundary between the Dalings and the Darjeelings was also considered as perfectly gradational by them.

The results of the detailed mapping carried out by the author have proved the views of some previous workers, that "the terms Daling Series and Darjeeling Gneiss may be applied respectively to the upper and lower portions of a great sedimentary succession, the lower part of which has been injected and metamorphosed by granite under stress" (Pascoe, 1961, p. 320). The disposition of the lithologic units as shown on the map of the area (Figs. 1 & 2) clearly point out that the

Dalings become more and more recrystallised as the Darjeeling gneiss is approached and the transitional passage between the two rock units is always through garnetiferous rocks. The phyllites and slates of the Dalings are succeeded upwards by a group of schistose rocks including chlorite-sericite-schists, golden and silvery mica-schists and at places by carbonaceous schists. The change from the unmixed Dalings, through the garnetiferous mica-schist to the Darjeeling gneiss, as recognised by the author, has been considered by Pascoe (1961), "as one from epigrade, through meso-grade to a hypo-grade (Katn-grade) metamorphism".

As regards the correlation of the Dalings and the Darjeeling gneiss to the rock types occurring in other parts of Himalayas, Bose (1875) correlated the gneissic rocks of Sikkim-Darjeeling Himalayas with the infra-silurian gneiss of the north-west Himalayas, where the Dalings are represented by the slate series, i.e., Griesbach's Haimantas of the Central Himalayas. Auden (1936) suggested, "the granites of Dwarabat, Dudatoli and Lansdowne in Garhwal Himalayas are taken to be equivalent to the igneous portions of the Darjeeling gneiss". Gansser (1964) considered these rocks " ... to be characteristic representative of late Pre-Cambrian to early Cambrian argillaceous sequence which we have already met in the western lower Himalayas (Simla and Dogra slates) and which may represent a marginal facies of the Vindhyans of the Peninsular shield area". Krishnan (1968) believes that, "the Dalings resemble Salkhalas. The non-calcareous part

is similar to Chandpurs which have also a close resemblance to the Cambrians. The calcareous part, on the other hand, resembles Jutoghs of Simla. On the whole they are considered as belonging to the Pre-Cambrian".

No such evidence is available on which the present author may differ from the opinion expressed by Pascoe (1964), Gansser (1964) and Krishnan (1968).

A. Darjeeling Series

The name'Darjeeling Series' is after the town of Darjeeling, the famous hill station in West Bengal.

Lithologic Unit

The Darjeeling Series is mainly represented by the igneous portions of the Darjeeling gneiss complex, which overlies the Daling Series as a result of inversion around the Darjeeling Himalayas. The prevalent strike of the gneiss is WNW-ESE. They often differ in their textures from fine to coarse to moderately coarse-grained. The mineral composition varies from band to band. The granitic rocks pass downwards into garnetiferous mica-schists. The biotite-gneiss of this complex sometimes shows augen structure. The segregation of felspars and quartz often gives a banded appearance to the rock. They vary from the quartz-felspar rich gneisses to garnetiferous biotite-muscovite gneisses. The garnetiferous varieties of biotite-gneisses are also very common. Sillimanite-biotite gneisses with or without garnet have also been encountered. The sillimanite gneisses

that occur southeast of Kalimpong, and northeast of Darjeeling, may represent the Kata phase of metamorphism as referred to by Ray (1947) and Gansser (1964).

Pegmatite and aplite veins from a few inches to a foot or two in width are very common in the granite-gneisses. Basic rocks in the form of sills and dykes are frequent in the Darjeeling gneisses. The dykes run NE-SW or E-W.

The quartz veins in the granite gneiss are frequent. Some of the veins also cut across the dykes and sills of basic rocks.

An important feature in the granite gneiss is the disseminated occurrence of sulphide ores located at two places in the fractured zones south of Algarah. The mineralisation was also noticed near the contact of the Darjeeling gneisses with the Daling series.

Age of Darjeeling gneiss and other granitic rocks

Since the age of emplacement of some of the granites has an important bearing on the source of mineralization of copper, lead and zinc, an attempt has been made to determine their absolute ages by radiometric methods.

The granitic rocks, supposed to be equivalent to Darjeeling granite-gneisses, frequently occur in the Himalayas extending from Hazara eastwards through Kashmir, Garhwal, Kumaon, through the area of the present investigations to Nepal, Bhutan and Assam Himalayas. Pebbles of Darjeeling granites have been found among the pebbles of the basal conglomerates in the Lower Gondwana rocks of the area. It

is, therefore, evident that these granites are older than the basal conglomerates.

The age of the granites by lead isotope ratios in feldspars and those in the whole rocks samples has been found to be 1760±60 million years. This age obviously places the granites in the Pre-cambrian. Potassium-argon ages of five muscovite and four biotite samples derived from the Darjeeling gneiss from various localities from eastern and northeastern parts of Darjeeling area have shown that their ages vary from 10 to 25 million years, which may be the age of metamorphism of the granites. Krumencher (1961), Wager (1965), Eremenko and Datta (1968) have also found from Rb/Sr and Sr^{86}/Sr^{87} ratios that the age of metamorphism is more or less/same as that determined by/K/Ar method.

The age of the tourmaline-granite which occurs in the northern part of the region beyond the study area, has also been calculated from the lead isotope ratios in feldspars, potassium/argon ratios, rubidium/strontium ratios in biotite and muscovite and thorium/uranium ratios. The age was found to be in the range of 20±10 million years and the average being 13 million years. This tourmaline-granite is therefore, of the late tertiary age and supposed to be the youngest since it has intrusive relation with all other older rocks.

B. Daling Series

General Statement

The term Daling Series was coined by Mallet (1875) after a

place known as Daling in the Darjeeling district, West Bengal. It occupies a large portion of the area, especially in the Legship-Soshing and Damthang-Temi, Peku blocks, and also those around Darjeeling and Kalimpong. The Series consists of rocks ranging from slates, phyllites to schists. Thin bands of quartzites were seen at many localities.

The earlier workers, including Mallet (1875), Bose (1891) and Gansser (1964) while giving a picture of regional structure of Sikkim and Darjeeling Himalayas.found that the 50 km long core of the large north-south directed domal uplift was formed of the Daling Series. This regionally simple picture is complicated by local disturbances. On the southern side of this structural dome the dip is south-eastern; east of Rangit river it is chiefly ENE to NE; west of the river the inclination is northwestern; and on the northern side as near Ralong the dip is mainly northern. Krishnan (1968) believes that "they form a large recumbent fold, thrust to the south. In the core of the fold are the Kanchenjunga, Paunri and some other massifs while Mount Everest is in its upper limb." The southern boundary between the Dalings and the gneissic rocks, which passes a little north of Darjeeling, was shown by Mallet (1875) to be faulted. However, it is a matter of great controversy and will be dealt separately. The eastern boundary passes through Gangtok and Western through Pemionchi.

The intricate geology of the Lower Himalayas of Sikkim and Darjeeling Himalayas was unravelled only after some clarity had been obtained of its complicated tectonics. The almost complete absence of

fossils in this part of Himalayas on the other hand leaves many stratigraphical problems unsolved.

This drawback in return casts some doubts on certain tectonic and stratigraphical interpretations. It is with these difficulties in mind that the geology of the area under investigation was discussed. The results of the investigation by the officers of the Geological Survey of India and by the author have shown that the 'sandstones and carbonaceous slates' included by Bose (1891) in the Dalings belong actually to the Damuda group.

Lithologic Units

The Daling Series in the area includes the following rock units :

1. Phyllites
   a) Slaty phyllites
   b) Chlorite phyllites with interbanded schists and quartzites with copper ores.
2. Quartzites
3. Slates
4. Garnetiferous mica-schists

1. Phyllites

The typical and most dominant among the Daling group of rocks in this area are the phyllites which range from slaty phyllites to true phyllites.

a) Slaty Phyllites

This rock is usually dark grey and sometimes purplish grey.

The slaty cleavage had been subjected to gentle puckers which plunge towards ENE directions with moderate angles.

b) Chlorite phyllites with interbanded schists and quartzites with copper ores

The type rock is a green chlorite-sericite-quartz phyllite grading into schists and is traversed by numerous quartz veins. The presence of numerous quartz veins along the schistosity plane imparts to the rock a streaky gneissose appearance. Some of these quartz veins also contain siderite and limonite. Usually the rock is dark grey in colour, but it assumes a greenish appearance when the chlorites become bigger in size. Puckering and grooving are, as a rule, more intense in this rock than in the slaty phyllites. Biotite is often noticed in this rock especially in certain bands along Legship-Soshring road.

The phyllites contain variable amounts of sericite and with the increase in the sericite content, they appear silvery. At some places the phyllites contain 1 to 20 cm thick lensoid intercalations of siliceous phyllites. Near the confluence of the Rangit river and the Malet Chu, one such band, 7 cm thick, contains some aggregates of sulphide minerals. Occasionally, the intercalations become quartzitic with the increase of quartz in them. The quartzite bands are so thin that most of them could not be plotted on a 1:31,680 scale map.

The rocks are largely mineralized by Cu-Fe ores which frequently occur in association with quartz veins emplaced along the

schistosity, shear planes and fracture cleavage of the rocks and their quartzites intercalations. There are also disseminations of some sulphide ores in the rocks. The quartz veins have two types of quartz, viz., i) grey and cherty, and ii) white and semi-viterous. The sulphide minerals are associated with the first type. The mineralised rocks are mainly light coloured, coarse-grained, dolomitized, silicified, sericitized, chloritized and talcose. Barren rocks are darker in colour, and fine-grained, less dolomitic and silicified than the mineralised phyllites. As a result of alteration extensive ferruginous stains are seen in these rocks. Silicification is indicated mainly by the replacement of carbonate minerals by jasperoid and by the presence of quartz veins.

Grey, almost flaggy, well-jointed quartzites is the other rock type of the Dalings. They are well exposed around Sikhip, Legship and Kalimpong. The quartzites vary in their colour from pink, white to light yellow. The texture is generally medium- to fine-grained. At some places these quartzites appear schistose with the appearance of sericite. Primary structures except bedding joints are rare.

3. Slates

The Daling slates are found to occupy different parts of Ranjit valley in the areas located north of Nayabazar. Calcareous bands were occasionally noted. Typically they are greenish to greenish-grey coloured rocks. Pebbly and gritty slates occur in a few localities like Sikhip, Mangwa and many other places in the northeastern

and southern regions.

4. Garnetiferous mica-schists

These rocks form a sort of transitional zone between the Daling Series and the Darjeeling gneisses and stratigraphically, they belong to the lowermost part of the Daling Series. Biotite and garnet are very common. Muscovite, kyanite and staurolite occur as minor constituents of the rock. According to Heim and Gansser (1939) the rock types belonging to this zone "show a striking resemblance to the crystalline para-zones of the lower Penninic thrust sheets of the Alps, especially to certain occurrences of the Canton Ticino, such as on Pizzo Forno".

C. Baxa Series

General statement

The Baxa Series was named by Mallet (1875) after the old Baxa Fort in the Western Doars. The series has been ever since a problem in Indian geology. Mallet (1875) defined Baxas as a Series of rocks some thousands of feet in thickness and comprising of variegated slates, schists, quartzites and dolomites. The previous workers' interest was only confined to the type area of Baxa Doars and the parts of southern Bhutan. The presence of Baxa Series in the Sikkim area was completely unknown till it was recognised by the author during the course of his present investigation.

Recently, however, the Geological Survey of India carried out some regional surveys in the area but the work is not yet published. The cardinal problems of stratigraphy, petrography and sulphide mineralisation in the dolomitic rocks of Baxa Series remained neglected. Almost all the previous workers restricted their investigations only along the road sections. Gansser (1964) admitted that, "Our own investigations along the lower road sections beginning in Phuntsuling have shown that most severe tectonic disturbances occur, and that a sharp division between Baxa and Daling formations is practically impossible. Only the lower Baxa section seems to outcrop along this part of foothills. It is, therefore, questionable to what extent we have to deal with normal sequences, how much of the outcropping profiles is normal or reversed, and how much is repeated by imbrication and faulting."

Lithology

The Baxas in the work area are differentiated from the Dalings on the basis of the presence or absence of carbonate rocks and variegated slates. The Baxas are sandwitched between the Damudas (Lower Gondwanas) and the Dalings - where both of these contacts are tectonic (Pascoe, 1959). The Baxa Series may broadly be differentiated into the following principal lithologic units:

1. Slates
   a) Predominantly non-calcareous
   b) Predominantly calcareous
2. Massive limestones (with occasional stromatolitic structures) and thin-bedded limestones (with occasional intercalations of calc-phyllites).

3. Dolomites and dolomitic limestones (talcose at places) with sulphide mineralisation

4. Quartzites

The Baxa group of rocks are prominently exposed along the Ranjit river section from Tatapani to Rishi and also on the left bank of the river downstream beyond Rishi. While the limestones, dolomitic limestones and dolomites constitute the sharp and rugged ridges, the calcareous slates and quartzites develop a slightly rolling topography as seen at Wak and around. The Baxa Series is surrounded on all sides by green to greenish grey slates, (sometimes gritty in nature) belonging to the Dalings. To the east of Tinkitam several patchy exposures of the Baxa rocks occur near Choreten. They extend farther north and north-west, and cross the Rangong Khola at an altitude of about 1,400 m.

The Nayabazar-Legship road section provides excellent exposures of these rocks between the 8th milestone and Tatapani, north of Rishi. This long outcrop of Baxas is interrupted by the Gondwana sandstones and slates for a distance of 1.5 km. A narrow and isolated wedge of Baxas is exposed at the Daling-Gondwana contact, north of Tatapani.

Brief lithological accounts of the various types of rocks belonging to the Baxa Series are given as follows :

1. <u>Slates</u>

The slates of the area can easily be grouped into the following lithologic types :

a) Predominently non-calcareous slates

The non-calcareous slates, which are dark in colour, form a prominent band towards the base of Baxa formation. They break into thin needle-like fragments. The black colour is perhaps due to the presence of some carbonaceous materials. Slates with pyrite bands of upto 15 cm thick have been located along the Nayabazar-Rishi road section, about 1/2 mile north of the 8th milestone. The slates often become cherty. Near Padam the slates are intruded by a 4 meter thick basic sill.

b) Predominently calcareous slates

The calcareous slates are dark grey, greyish blue to purple in colour, and show well developed slaty cleavages. They show the presence of thin intercalations of limestones, which are often nodular.

A variety of slates, having intercalations of dolomite prominently crops out at the Rishi-Rahu ridge and the Nak area. It is thinly laminated, fissile and pale grey to purple in colour.

2. Massive limestones (with occasional stromatolite structure) and thin-bedded limestones (with occasional intercalations of calc-phyllite)

The outcrops of thin-bedded limestones and intercalated calc-

phyllites are rather rare. Such limestones are exposed only in the Sikhip and Rishi areas. They are hard, compact, well-bedded and well jointed and vary in colour from grey, greyish blue, purple, pink to dull white. The individual calcareous bands are 1 mm to 5 mm thick. Minor folding, jointing and faulting are common features in the limestones. Some of the limestones are typically silicified with thin interbands of chert.

It is often difficult to demarcate the contact between the thin bedded limestones, and the limestones with algal stromatolites. The contact appears to be mostly irregular and sometimes gradational. The occurrence of algal limestones are not very common and only at two localities, viz., 1) north of Rishi along the western bank of Ranjit river, and 2) at Sikhip, on the eastern bank of Ranjit river, they have been noted. They occur overlying the calcareous phyllites and slates.

The dolomitic limestones with occasional stromatolites are medium to fine-grained and intensely jointed. They are highly cherty due to the presence of lenticular bands of chert upto 15 cm thick. The chert bands are commonly parallel to the bedding traces in the dolomitic limestones. The surface of these limestones sometimes becomes extremely corrugated due to differential weathering of the chert bands, which stand out 2-6 inches high on the surface of the limestones. Their weathering is of 'elephant skin type'.

The dolomitic limestones show the development of the 'laterally

space-linked' type of hemispheroidal bodies. The space between different structures is greater than the diameter (2 cm) of the individual structures. The laminae of these stromatolites are pink in colour, and on weathering, they give rise to a reddish film or coating on the surface of limestones. According to Logan, Rezak and Ginsburg (1964) the algal stromatolites of such type belong to the genus Collenia.

3. Dolomites and dolomitic limestones (talcose at places) with sulphide mineralisation

The dolomites and dolomitic limestones, which are predominately exposed in the Ranjit river section, north of Rishi, and also on the northern face of the Tinkitam-Subuk ridges, form the most conspicuous horizon of this group. They are generally dark coloured (grey, greenish grey, greenish blue and black) to light coloured (light grey and creamy white) massive rocks; a pinkish to purple variety, somewhat flaggy in nature, occurs as intercalations. They are compact and saccharoidal in character. Usually they are highly siliceous, and with the increase in silica contents, the rock tends to become quartzite or dolomitic quartzite, which effervesces with acid very feebly.

South of Rishi the dolomites are greenish grey to grey and purple coloured. They have intercalations of quartzite and greenish coloured calcareous slates with calcareous stringers. The dolomites are highly jointed.

In conformity with the regional structure, the dolomite group of rocks dip with moderate to high angles in the northerly or northeasterly direction. Foldings of various magnitudes from minor to major recumbant types are quite common. The lead deposit , which occur north of Rishi, is essentially associated with the light coloured (creamy white) and talcose variety of dolomitic limestones which are highly silicified. The barren rocks are dark coloured, fine-grained and less silicified and dolomitic than the mineralized rocks.

4. Quartzites

The quartzites are thick-bedded to massive, light coloured with shades of grey, green, pink, white to light yellow colours, fine to medium-grained and sometimes feldspathic in nature. Since the rocks, in general, are mineralogically and texturally mature, they may be termed as orthoquartzites. There are also intercalations of dolomitic quartzites, the thickness of which varies from 5 cm to 1 m.

The dolomitic quartzite bands show sedimentary structures like ripple marks, gradded beddings and cross-laminations as at Mangwa, near Sikhip.

They are so frequently jointed and disturbed that it sometimes becomes a real problem to differentiate between the joint plane and the bedding plane of the rocks. The quartzitic rocks pass conformably into slates.

Age of the Baxa Series

Introduction

Earlier workers correlated the dolomitic rocks of Baxa Series

of the type area with that of the adjoining area in Eastern Himalayas, and the parts of Western Himalayas mainly, on the basis of the lithological resemblance and apparent stratigraphic relationships. Most of the workers including Mallet (1875), Pilgrim (1906), Lahiri (1941) and Gansser (1964) debated on the stratigraphic position of these rocks. Some grouped them with the pre-Cambrian while others emphasized their similarity with the 'Krol Series' of the Simla Himalayas. Pilgrim (1906) described the section between Manas and Kuru Chu and gave an almost similar sequence as that of the tentative sequence compiled by Gansser (1964). But he (1906) preferred to include part of formation at Sinchu La as belonging to the lower stage, and the Baxas as the Upper stage of the Daling Series. Gansser (1964) believes that Jaintia quartzites form the base of Baxa Series.

Nautiyal et al. (1964) proposed a Permo-Trias (?) age for the Baxa Series of Bhutan Himalayas, and correlated it with the Blaini-Krol-Tal Series of the Kumaon Himalayas. According to those authors, the Series is in part a marine equivalent of the Gondwana System. O'Rourkee (1962) suggested a Permo-Carboniferous age to the banded iron ore deposits of Baxa Series occurring at the foothills of Eastern Himalayas. Gansser (1964) commenting on the views of O'Rourkee (1962) expressed that "If this is true a Permo-Carboniferous age could be suggested for the whole of the Baxa Series, but this possibility favoured by O'Rourkee is still open to much doubt". He (1964) further states, "It is still questionable if they should be correlated with the Krols or with the Deoban-Tejam belt of the Kumaon Lower Himalayas.

I would prefer the later alternative, but must admit that such a long distance correlation is more than questionable".

Stratigraphic position of Baxa Series

Within a stretch of about 30 km of the road from the Nayabazar to Tatapani along the Ranjit valley, the Baxa dolomites are exposed at several places and are folded together with the sandstone-shale sequence of the Gondwana System. Detailed geological study of a part of the road from Sikhip to Tatapani was undertaken on a scale of 1:1000 (Fig. 4) to find out the stratigraphic and structural relations between the dolomitic limestones and the Gondwana formations exposed in this section.

In between these two formations there is usually a pebbly slate zone in the conglomerate beds, which is included in the lower portion of the Gondwana sequence. One of the ubiquitous components of the pebble assemblage is dolomite or dolomitic limestone, the lithology of which appears to be similar to that of the Baxa dolomites and dolomitic limestones exposed in the area. This fact tends to place the Baxa dolomitic limestones with a stratigraphic horizon, older than the Gondwana group of rocks.

Some of the exposed contacts of the Baxa dolomite with the pebbly slate appear to be very much disturbed probably due to shearing and brecciation. Near Tatapani these features are conspicuous. Another contact, about 1.5 km north of Rishi, is marked by a wedge of limonitized zone having a maximum thickness of about 2 m.

This zone is characterised by a certain amount of silicification and pyritisation. Similar other occurrences have also been recorded from the Sikhip area. If this criterion is considered enough to establish a tectonic contact, it may be said that the dolomitic limestones were thrusted over the Gondwanas.

If, however, the above criterion does not provide sufficient evidence of thrusting, the possible alternative will be to describe the Gondwana-Baxa dolomitic limestone contact, north of Rishi, as one sedimentary sequence with the dolomitic limestones overlying the pebbly slate. This is supported by the occurrence of normal sequence on either side of the contact between the Gondwana and the dolomites. The Gondwana sandstone-shale-pebble slate formation shows faint gradded bedding, which points to the normalcy of the sequence, whereas the convolutions within the dolomites, or dolomitic limestones, and the quartzites show the normal sequence of the Baxa beds.

In such a case, the presence of dolomite boulders, and pebbles within the boulder bed of Tatapani and elsewhere may necessitate the existence of one or more dolomitic horizones older than the exposed Gondwana beds in this section. A 50 m thick dolomite band, about 40 m NW of Tatapani may be one of such bands. It shows clear gradation into the typical Daling phyllites further north. But the primary sedimentary structures point to the reversal of the sequence indicating that the Dalings are older than the Baxas.

The presence of the algal stromatolites (genus Collenia) in these dolomites and dolomitic limestones is significant and has a

great bearing on the age and correlation of these limestones. Based on the presence of such algal stromatolites Valdiya (1962, 1965) and Gansser (1964) have correlated the Shali limestones of the calc-zone of Pithoragarh with the Deoban limestones of Upper Pre-Cambrian to Cambrian age. Ali (1970) also reproted the presence of genus Collenia in the dolomitic limestones of south and north calc-zones of Bageshwar and placed them between the upper and lower Cambrian.

Therefore, on the basis of the occurrence of similar algal stromatolites (genus Collenia), the dolomitic limestones of Buxa Series of west and south Sikkim may be correlated with the calc-zone of Bageshwar area in the Almora Himalayas and accordingly, they may be placed between the upper and lower Cambrian. This statement is further supported by a more or less similar stratigraphic and lithologic set-up, and the similar types of sulphide mineralisation in these two widely separated regions of the Himalayas.

D. Damuda Series (Gondwana System)

General Statement

An interesting feature of the area is the occurrence of lower Gondwana rocks in the form of a 'window' in the Ranjit valley (Figs. 2 & 11). Their junctions with the Buxas and Dalings are faulted. The rocks belong to the Damuda Series and consist of pebbles and gritty slates, sandstones, carbonaceous shales, and occasional thin coal seams. In the Ranjit valley the rocks occur around Tatapani and Rishi and from south of Sikhip to as far as north of Nayabazar. At higher altitudes,

the Damudas occur on the range of hills between Rangong, Tinkitam, Damthang and Namchi. In most of the areas where the boulder beds and pebbly slates are prominent, the junction is prominent. The Damuda rocks in this area are less metamorphosed than those at Tindharia in the Darjeeling district. Gondwanas are also exposed north of Tindharia and are thrusted against the Siwaliks. They are wedged between Dalings and Siwaliks (Fig. 1) and are traceable throughout the lesser ranges of Darjeeling Himalayas.

Lithological Units

The following lithologic units are recognised:

1. Boulder beds, pebble slates and shales
2. Sandstones

1. Boulder beds, pebble slates and shales

The basal portion of the Damudas is represented by boulder beds and pebbly slates. The pebbly slates appear to occupy a distinct horizon in between the Damuda sandstones and the Baxa limestones. The best exposures of this pebbly horizon are in the Ranjit valley river section near Tatapani where it is almost 120 m thick. Other important exposures of this rock are i) at Tinkitam village, ii) on the lower slopes of Rinchingpong hill, iii) in the Rishi Khola section near Rishi Bazar, iv) in the Rangong Khola, to the north of Lingyong and near Naya Bazar and v) north of Tindharia in Darjeeling area (Figs.1 & 2).

Different sizes of rounded, elliptical, and sub-angular pebbles and boulders of granite, granite-gneiss, black slates, quartzite, dolomite, dolomitic limestones and phyllites occur in a slaty matrix

of the boulder bed at Tatapani. The matrix is fine-grained and is composed of quartz and sericite and occasionally with a little authigenic chlorite and also some calcite. The size of the pebbles in the boulder beds varies from 0.5 cm to as large as half meter in diameter.

Thin boulder beds containing large boulders of dolomite occur also on the western slopes of the Tinkitam range. The pebbles in the slates are mainly of quartzites, phyllites, dolomites, dolomitic limestones, granite and gneisses. A part of the matrix is composed of shales, which are greenish in colour, micaceous or calcareous, and usually break-up into thin pencil-like or prismatic fragments. The shales are sometimes graded into sandstones or greenish or greenish-brown colour.

2. Sandstones

The sandstone,which is the dominant member of the Damuda Series, is usually of dark grey to greyesh blue colour, sometimes gritty and coarse to medium grained. It is well bedded, occasionally massive, and highly jointed. The quartz grains are often slightly flattened and due to which the sandstones appear slightly foliated particularly,near their contacts with the dolomites and dolomitic limestones of the Baxas series. White quartz veins occur as joint fillings. The sandstones alternate frequently with thin beds of carbonaceous shale which occasionally contain fragmentary plant fossils. They often have thin coal seams upto a maximum thickness of about 2 cm around Namchi, Tatapani and Nayabazar. Sometimes the seams of graphitic coals, as near

Nayabazar, show partings of lensoid quartzitic sandstones.

About 230 meters north of the bridge on the Ranjit river at Nayabazar, the sandstones have intercalations of grey coloured dolomite with calcareous and non-calcareous slates, the width of the outcrop being about 150 m along the road. In general, these have discordant structural relations with the surrounding Damuda rocks. These rocks represent a thrust sheet of the Raxas (Fig. 2). North of bridge, on Ranjit river, and south of this thrust sheet, the Damuda rocks show a number of minor folds causing repitition of beds. The axes of these minor folds trend E-W. Just west of the bridge on the Ranjit river at Nayabazar, in the road cutting, a gritty sandstone containing angular to sub-rounded pebbles of quartz occur. The gritty sandstone is intercalated with slaty bands. This gritty bed was also encountered on the Nayabazar-Namchi road about 1,000 m NE of the same bridge over the Ranjit river (Fig. 2). Also they are exposed near Tindharia (Fig. 1). The gritty sandstone is restricted significantly to the upper part of the basal boulder beds. This gritty sandstone laterally grades to sandstones. Frequently the sandstone grades into siltstone and shows the development of gradded bedding. Cross-beddings have also been noted in the sandstones, but none of these characters are well preserved.

Age and correlation of Gondwana rocks

Ghosh (1953) has reported the presence of plant fossils (Glossopteris, Vertebraria and Schizoneura) in the Damuda rocks at

Nayabazar and Khemagaon and several other places. The Series with pebble beds below and sandstones with coal seams above, have been correlated with the Talchir and Barakar Series (lower Gondwana) respectively, belonging to the Permo-Carboniferous age.

E. Siwalik System

The word Siwalik was first used by Emperor Babar (see Raina, 1971) in his remarks, and it means the edge of the roof of Siva's dwelling.

The Siwalik formations appear north of Siliguri near Sevok. They have been mapped as a belt from west of Tista river to the west of Jaldhaka river. The inner boundary of Siwaliks or its contact with the older rocks is defined by the 'Main Boundary Fault'. Wadia (1957) suggested that, "the Main Boundary Fault is not an ordinary fault or dislocation which limits the boundary of the Siwaliks, but it marks the original limit of deposition of these strata against the cliff or foot of the then existing mountains beyond which they could not extend. It was supposed that subsequently this limit had been further exphasized by some amount of faulting".

The boundary fault is considered to be the successive limit of deposition against the advancing foot of the Himalaya (Wadia, 1957). Heim and Gansser (1939) recognised the Main Boundary Fault as a thrust, with the Siwaliks at the interior contact and the older Himalayan formations overriding the former in the border zone. Pascoe (1964) also believes, "There can be little doubt that these older rocks have

thrusted over the Tertiaries along the equivalent of the Main Boundary Fault".

In the area mapped by the author, a section of the Gondwanas (Damudas) all along separates these Siwalik rocks from the Dalings (Fig. 1).

Lithologically, the Siwaliks of this area are made up mainly of soft massive sandstones with indurated clays to which Mallet (1875) mentions as "clunchy beds". The section, measured from near Sevok bridge upwards, shows about a 60 m thick layer of soft, highly feldspathic, slightly micaceous, medium-grained, white to light buff coloured sandstones with black mineral specks. The sandstones are interbedded with nodules of marl and clays. They are overlain by another unit of about 1,750 m thick grey sandstone with occasional marly layers. This is followed upwards by about 350 m thick buff to grey coloured sandstones with prominent conglomerate bands containing quartz and rock pebbles of various sizes.

This conglomeratic sandstone is in direct contact with the Gondwana and forms the base of Siwaliks. The pebbles in the sandstone, which include pebbles of white quartz gneisses and schists, are found to be well-rounded with a maximum diameter of 2-3 cm. The interbanded clay in the basal part of the sandstone is highly ferruginous, and sometimes, a zone with impure brown hematite occurs near the base. Mallet (1875) has found the continuity of such a ferruginous horizon right upto Nepal. The sandstones are frequently current bedded. Fossil plants and stringers of lignite are also found in the sandstones.

Chapter III

PETROGRAPHY OF ROCK TYPES AND METAMORPHISM

PETROGRAPHY

Through petrographic, petrogenetic and geochemical studies of various rock types of the area, an attempt has been made to distinguish between the wall-rocks and the country rocks. The details are given under the following heads :

I. Host rocks of lead-zinc ores
II. Host rocks of copper ores
III. Other non-mineralized rock types of the area

While the lead-zinc deposits are essentially associated with the Baxa Series, the copper ores are found mainly in the Daling Series, and also partly in the Baxas.

I. Host rocks of lead-zinc ores

The lead-zinc deposits of Rishi occurs in the carbonate rocks of Baxa Series. These country rocks have been subdivided into two distinct parts, viz., A) mineralised or productive part and B) sterile or unproductive part.

A. Mineralized part

Dolomitic limestones (Plates XII, Fig. 3; XIII, Figs. 1,2,3,4; XIV, Fig. 1).

The country rocks in the mineralized part are essentially dolomitic limestones which are often highly silicified. They vary in

texture from place to place, and contain veins, specks or disseminations of lead and zinc minerals. They are medium-grained rocks and are composed primarily of calcite, and dolomite. Quartz and some argillaceous materials are the essential non-carbonate constituents. Quartz of two generations is found. Some of the dolomitic varieties of limestones show a tendency of having abundance of accessory minerals. They are therefore, cherty and argillaceous.

The mineralogical characters of the following constituents are given in detail:

Calcite - Calcite is the principal constituent of the dolomitic limestones. Its crystal shape is prismatic, granular or rhombohedral and the grain-size is fine. Generally it is a major constituent of the rock matrix. The grains are somewhat equigranular, anhedral and cloudy, and their predominant size is less than 0.15 mm in diameter. Polysynthetic twinning is very common. Irregular fractures are the most prominent features. Some of the calcite grains are clouded with dark inclusions of carbonaceous material. None of them possess any sign of organic matter. Excepting these inclusions there are no traces of organic remains.

Silicification of calcite is a prominent feature. The boundaries between the crypto-crystalline silica and calcite grains are not very well demarcated and show an 'eating away' phenomena due to their partial replacement by quartz as well as dolomite.

Dolomite - It is an essential mineral of the dolomitic limestones. In order to distinguish dolomite from calcite, Otto's microchemical test (Krumbein and Pettijohn, 1938; Cannal, 1947 and Friedman, 1959) was performed. The colour of dolomite remained unaffected whereas that of calcite turned brownish-red.

Porphyrotopes of dolomite occur in a fine-grained matrix of calcite. They are characteristically euhedral to sub-hedral and rhombic in form. Isolated crystals of dolomite are commonly euhedral, particularly when they occur in a matrix of calcite. Twinning and rhombohedral cleavage are characteristically present. The micro-voids in the porphyroblasts are filled up by crypto-crystalline silica (jasperoid) and secondary calcite. Many dolomite crystals are made up of zones of varying iron content, the ferriferous zones have a brownish tinge.

Dolomite is sometimes replaced by silica either partly or wholly. Ocassionally, the replacement is pseudomorphic.

Silica - This is one of the most important constituents of the rock. Two generations, corresponding to the crystalline and the crypto-crystalline varieties, have been recognised.

a) Quartz : The crystalline variety of silica is closely associated with calcite, but it shows no replacement relations with primary calcite nor any interlocking feature with primary calcite. This may therefore be of primary origin. It is free of any inclusion and

displays strain shadows. This variety is rather uncommon and constitutes hardly 5 per cent in the dolomitic limestones.

b) Jasperoid : Jasperoid, a cryptocrystalline variety of silica, is commonly present in these rocks and replaces both calcite and dolomite. This variety of silica is intimately associated with ore minerals.

Textural interpretation

The limestones show typical 'replacement textures'.

The replacement textures in limestones have been reported by several workers (Hewett, 1928; Carozzi, 1960; Murray, 1960; Friedman, 1965; Friedman and Sanders, 1967; Ali, 1970). Similar textures are found in the dolomitic limestones of the area under investigation where the porphyrotopes of dolomite are embedded in a fine-grained matrix of calcite. The contacts between the pairs of minerals such as dolomite-jasperoid, calcite-jasperoid, calcite-dolomite, are irregular. They show 'eating away' phenomena which is a typical feature of replacement texture. In many cases the shape of dolomite crystals is retained very well by the pseudomorphous jasperoids. Due to incomplete replacement in some cases, relict grains of calcite and dolomite are found embedded in jasperoids. However, some of the dolomite crystals are not perfectly developed and contain minute random inclusions. The incomplete dolomitization not only produces a scattering of dolomite euhedra in an unaltered calcite groundmass but may also generate a mottled texture. The patchy colour pattern referred to as 'mottling'

is produced by the presence of contrasting matrix and is always related to the process of dolomitization (Boyle, 1953; Osmond, 1956). Chams (1954) and Pettijohn (1957) believed that mottling may be a product of solid solution of magnesium and calcium carbonates. Many of the big calcite grains and the associated calcitic matter are either partly or wholly changed to dolomite whereas the surrounding groundmass is practically unaffected. Where the alteration is incomplete, numerous isolated rhombs of dolomite are developed, but where it is more advanced, the crystals interfere and show irregular outline.

The sharp interpenetration of dolomitized and undolomitized material shows that it could have been caused only by the irregular advance of magnesium in the hydrothermal solutions.

Another interesting feature is the increase of porosity of the dolomitic limestones. As the conversion of calcite to dolomite occurred molecule for molecule, it caused reduction in volume and hence a relative increase in porosity of the dolomitised rocks.

It is also evident from the fine-grained and anhedral nature of the calcite that the medium-grained dolomitic limestone forming the wall-rocks were originally of a fine-grained or micritic texture (Folk's terminology, 1959).

The texture was changed from micritic to porphyrotopic by the later processes of dolomitization and silicification. According to Van Tuyl (1916) and Friedman (1965), the 'porphyrotopic texture' of dolomitic limestones is a clear indication of an incomplete

dolomitization which is further supported by the presence of mottling effect. Several workers including Hewett (1928), Lovering (1949), Carozzi (1960) and Ali (1970) have reported that silicification followed dolomitization in similar cases. This is true in this case also. The presence of jasperoid in the voids and vugs within the dolomite crystals indicates that silica was introduced after dolomitization. Silicification was followed by the lead-zinc mineralisation as is evident by the presence of veins of lead and zinc sulphides in jasperoid. Often comb structure is formed in the veins. Friedman (1965) says "Where sulphide minerals are associated with epigenetic dolomites, dolomitization of the limestones seems to have preceeded precipitation of the sulphides".

Based on the above observations of textural and structural relationships of various minerals, the following sequence of events preceeding ore deposition may be drawn:

1. Dolomitization (incomplete)
2. Silicification (by jasperoid)
3. Pb-Zn mineralisation

Almost similar sequence of events has been reported by Rasul and Ali (1970) for the Pb-Zn-Cu-bearing dolomitic limestones of Almora and Pithoragarh districts of Kumaon Himalayas.

The process of dolomitization and silicification have thus played an important role in changing the original texture and composition of the fine-grained or micritic limestones (the country rocks) to the

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medium-grained dolomitic-limestone (the wall-rocks). The extent of dolomitization and silicification is clearly evident from the modal composition of these dolomitic limestones (Table 2). A linear pattern is shown in the variation diagram (Fig. 12) between calcite and dolomite and the jasperoid content. The variation diagram shows that the high content of jasperoid is associated with low content of calcite and dolomite and vice versa. This proves that under such conditions jasperoid is formed at the expense of calcite and dolomite (Wallace, 1913; Van Tuyl, 1916; Canal, 1947; Carrozi, 1960).

B. Unaltered country rocks

The unaltered country rocks of Pb-Zn ores are mostly limestones. Small beds of slates and quartzites are usually associated with these rocks. Several varieties of limestones were recognised.

Limestones (Plate XII, Figs. 1, 2 & 4)

The limestones are fine-grained and greyish in colour. Based on the composition and texture, the rocks are classified into :

a) Microsparites : (Folk's terminology, 1959). The microsparite is mainly composed of recystallized calcite with a little quartz. Calcite grins are fine-grained, equi-dimensional, xenotopic and brown in colour. Th texture is somewhat mosaic due to interlocking of calcite and qurtz grains. No allochems were observed, which seem to have been roved by recrystallisation.

b) Stromatolitic limestones : They are micritic and composed of

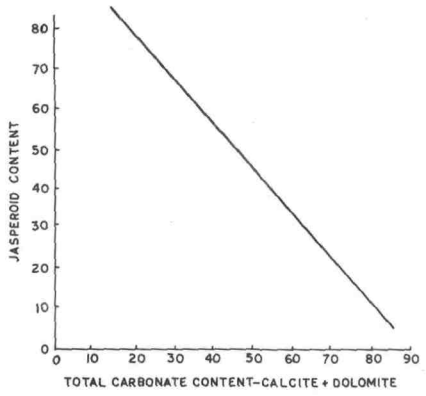


FIG. VARIATION DIAGRAM OF CALCITE, DOLOMITE AND JASPEROID IN THE DOLOMITIC LIMESTONES

Fig. 12

Table - 2 Modal composition and mineralogical characters of dolomitic limestones, Rishi area.

Sample No.	Calcite %	Dolomite %	Quartz %	Cryptocryst. %	Opaques %	Misc. %	Description	Important microscopic features
1	56.5	15.0	0.65	27.95	0.5	-	Silicified dolomitic limestone	Fine matrix of calcite with embedded dolomite crystals. Veins of silica common.
2	11.5	60.0	3.5	22.65	0.45	-	Silicified dolomitic limestone	Dolomite crystals in fine grained calcitic matrix with veins of quartz.
3	6.39	70.5	2.0	20.30	0.42	Talc 0.5	Silicified dolomitic limestone	Calcite is replaced by dolomite. Jasperoid filled the voids, and veins with galena ore.
4	59.4	17.7	3.0	18.8	0.75	-	Silicified dolomitic limestone	Eating away phenomenon is very common. Lead-zinc Ores are closely and intimately associated with jasperoid.
5	50.95	24.5	1.35	22.45	0.33	Fibrous calcite 0.1	Silicified dolomitic limestone	Fibrous calcite and jasperoid commonly filled the vugs and voids. Replacement texture distinct.
6	16.65	5.45	-	76.5	0.4	Talc 0.1		Silicification is of a high order. Relict veins and crystals of dolomites in calcite matrix.
7	50.95	24.35	1.25	22.6	0.44	-		Replacement texture distinct. Jasperoid veins along euhedra of dolomites common.
8	68.95	8.35	2.0	20.3	0.42	-		Replacement texture common. Jasperoid veins replacing calcite and dolomite.
9	9.2	27.7	-	62.5	0.6	-		Galena ore associated with jasperoid, which has replaced calcite and dolomite. Eating away phenomenon very common.
10	5.1	16.4	-	77.8	0.65	-		Highly silicified. Only a few relict grains of dolomite scattered in calcite matrix.

megascopic alternating bands of concavo-convex laminar structures. Under the microscope, no such feature could be detected. The rocks are essentially composed of recrystallized calcite and occasional dolomite.

c) Micrites : This variety is composed of micro-crystalline calcite, with about 20 per cent non-calcareous matter, chiefly consisting of fine-grained, silt grade quartz and a small amount of argillaceous material. Silicification is also common in this rock. The silicification and its effects on the wall-rocks and the country-rocks are presented in the table given below:

Wall-rocks	Country-rocks
Lead-zinc bearing medium-grained, silicified carbonate rocks	Silicified and barren fine-grained carbonate rocks
1. Dolomitization prior to silicification.	1. No dolomitization prior to silicification.
2. Silicification along veins, veinlets, fractures and vugs	2. Veins and vugs free from silicification, but sometimes bands of jasperoid are formed.
3. Variation in grain size of jasperoid is prominent, and varies from euhedral to subhedral, with a size ranging from 0.55 to 0.75 mm in diameter. Grain size of jasperoid associated with galena ranges upto 5 mm. in diameter. Jasperoid in vugs, veins and voids is responsible for the replacement of carbonates which are always finer than the former.	3. No variation in the grain size of jasperoid which is crystalline to aphano-crystalline.

Slates

The slates are fine-grained, greyish blue to purple in colour and show a well-developed slaty cleavage. They have some tiny round to

elongate grains of quartz and feldspar with chlorite, hematite, biotite, magnetite and some dark bands, perhaps, of carbonaceous matter. Zircon in the form of rounded grains is the main accessory.

Quartzites

The quartzites are light coloured, fine- to medium-grained rocks. Sometimes they are feldspathic or dolomitic. The colour varies from grey, green, pink, white to light yellow. They are silicified and intercalated with chert bands, and occasionally show primary sedimentary structures like ripple marks, graded bedding, cross-beddings, etc.

Thin section study of these quartzites shows that they are essentially orthoquartzites composed of quartz, chert, sericite and chlorite. Tourmaline and zircon are found as accessories. Porphyroblasts of quartz are embedded in a matrix of chert, dusty iron oxides and sericite. Quartz comprises about 96 to 99 per cent of the rock. The texture of the rock is mosaic. Inclusions of tourmaline and zircon occur in the colourless and sub-rounded grains of quartz. The size of quartz grains varies from 0.25 to 2.0 mm in diameter. Undulose extinction and fracturing of the grains have also been detected. The quartz grains are generally elongated and have a preferred orientation. Marginal granulation and recrystallisation have affected their detrital shape and outline. The matrix of the quartzite is mainly composed of crypto-crystalline silica, which varies from 6 to 28 per cent of the rock. The silica is mainly chert and have a mosaic texture. Next to chert is the colourless and flaky sericite which constitutes4 to 11

per cent of the fine matrix in the quartzite.

The mineral assemblage of the rock suggests low grade of metamorphism comparable to clastic mica zone of Harker (1939).

II. Host rocks of copper ores

The mineralization of copper is mainly restricted to the phyllites, schists and slates of the Daling and Baxa Series. Most of the wall-rocks, which are highly altered, show considerable variations in their petrographic characters. The host rocks show sharp mineralogical variations within short distances. The sulphide mineralisation is largely associated with the quartz veins that occur along the foliation and shear planes, joints, and fracture cleavages in the country rocks.

A. Mineralised part

The petrographical description of the rock types is as follows:

Chlorite-phyllites (Plates XIV,Fig.4, XV,Fig.3, XVI, Fig.1)

The chlorite-phyllites belonging to the Daling Series, are the common host rocks of copper in the area. They are intimately associated with impersistent bands of quartzites and schists and at places like Rangpo, Pachikhani, Kalimpong and Peku interbanding of these rocks are common. Sometimes sills of basic rocks alternate with bands of chlorite-phyllites.

Typical copper-bearing chlorite-phyllites are found at Legship

and at many other localities in the area. The type-rock which is a green variety of chlorite-phyllite, is often highly sericitic and quartzitic. The colour of the rocks varies from green to greyish brown and with the increase of sericites the rock assumes a silvery appearance. They are thinly foliated and fissile in nature. Sometimes the presence of quartz veins impart a streaky gneissose appearance to the rocks, as seen at Pachikhani. They grade into quartz-schists which with the increase in quartz content become quartzose and finally pass into pure quartzites.

Mineral composition

The rocks are mainly composed of chlorite, quartz, muscovite, and sericite and of accessory minerals like tourmaline, iron ores, etc. Muscovite and chlorite together make up nearly 90 per cent of the bulk. Some gradational types are found due to variation in the proportion of these two minerals but chlorite remaining always predominent.

Quartz

Quartz occurs in the form of large detrital grains (e.g., in quartzose phyllites), but also as small equant grains.

With an average of 0.1 mm diameter the grain size becomes coarser in the recrystallised clots. The grains are sometimes thoroughly crushed into finer size with sutured contacts and strong undulose extinction. The medium sized grains are equant, completely strain-free and represent recrystallised quartz. Sometimes, there are

rock
thin veins of quartz along the/foliation but occasionally cut across it. Dusty inclusions, arranged transverse to the major foliation, are seen within large detrital quartz grains. The coarser grains of vein quartz with strong fan-shaped undulose extinction, sometimes show marginal granulation. Jasperoid and chert are occasionally present in fracture veins. The grain size of quartz increases towards the highly biotitized zones.

Chlorite

Chlorite appears more or less uniformly distributed in patches and shreds. Formation of a major part of chlorite from biotite is evident. The optical parameters of chlorite suggest that the species is burusvigite, a ferruginous variety of chlorite. It is found in Peku, Legship and in other copper ore localities of Darjeeling district. Pleochroism is from dark green, yellowish green to pale yellow ($X>Y>Z$); R.I.-β = 1.646 to 1.649, and optically negative in some of the ore deposits in the eastern areas at Rangpo and Panchikhani. Two other varieties of chlorite, derived from biotite, which are found at Rangpo and Pachikhani, are pleochroic from pale yellow to yellow green ($X<Y<Z$); R.I. - β = 1.649 $\pm$ 0.002; their birefringence is 0.004 approximately. One of them (rumpfite) is optically positive and the other (delessite) is negative. The petrological identification of these species of chlorite has been confirmed by their X-ray analyses.

Delessite is generally found in the mineralised zone. While away from the mineralised zones rumpfite is predominent. But this cannot be generalized as reversions are also oberved.

Muscovite

The average length of muscovite flakes is 0.015 mm. The size of muscovite increases towards biotite zones in the northern and eastern parts of the areas, where it attains an average length of 0.75mm. Sericitization of muscovite crystals is a prominent feature in these phyllites.

Tourmaline

It is an important accessory mineral and three varieties are recognised on the basis of different pleochroic schemes.

i) E = colourless
   O = brown

ii) E = pale yellowish brown
    O = dark brown

iii) E = colourless
     O = bluish grey

These varieties of tourmaline are prominently developed only in the northern and eastern areas.

Talc

Talc is another important and major accessary mineral which sometimes imparts a soapy feel to the rocks and is typically found in the ore zones. At Rangpo the percentage of talc in the mineralized zone becomes so high that the rock may be called "talcose-chlorite-phyllite".

Biotite

Biotite, which is also present in a very minor amount, has a pleochroic scheme -- light yellow, brown to dark brown ($X < Y < Z$); R.I. - β = 1.652 to 1.670. It is a leached variety of biotite and

resembles siderophyllite in its optical properties.

Rutile

Clusters of the rutile needles are characteristically found in the altered rocks close to the ore deposits.

Other minor accessory minerals include feldspars, zircon, apatite and graphite, or carbonaceous materials. Sometimes the percentage of graphite or carbonaceous material increases so much that the rock becomes carbonaceous phyllite. Such types are found in Rangpo and Pachikhani areas.

The mineral assemblage of the rocks indicates that their metamorphic grade is comparable to the chlorite-muscovite subfacies of green-schist facies.

Chlorite-biotite schists (Plates XIV, Fig.3; XV, Fig.4; XVIII, Fig.3).

The chlorite-biotite schists are mostly found as wall rocks in south and southeastern parts of Darjeeling district and typically confined to the areas lying northeast of Darjeeling Himalayas. Garnet bearing chlorite-biotite schists are found only at three localities, viz., Rangpo, Peku and Pachikhani. These schistose rocks also belong to Daling Series.

Megascopically the rock is coarse-grained, roughly schistose and grey, light brown to yellowish and greenish brown in colour. At many places they have a silvery appearance.

These schists are made up predominantly of dark brown biotite flakes showing all the stages of alteration into chlorite. Bands,

lenses and veins of quartz often occur in them.

Garnet, wherever present, occurs as small reddish brown and rounded crystals, which are visible in hand specimens. Significant amounts of tourmaline, sphene, and very minor amounts of plagioclase feldspars, talc, apatite and some iron-rich carbonates are present.

Biotite

Biotite is the most prominent mineral in the rock and is commonly coarse-grained. Various stages of alteration of biotite to chlorite are common. There are also some relict hornblende which have largely altered into biotite.

The biotite has the pleochroic scheme, x = pale brownish yellow, y = brown, z = very deep brown ($X < Y < Z$); R.I. ($NY = NZ$) - 1.672 ± 0.002.

The biotite in the garnetiferous chlorite-biotite schists shows, however, an unusual colour and pleochroism: x = almost colourless, y = green, z = deep greenish black ($x < y < z$). It may be noted that the biotite from the non-mineralized schists (country rocks), however, shows the usual pleochroism but has a higher R.I.

Chlorite

In all the cases chlorite has been found to have been derived from biotite. In the garnetiferous rocks, some garnets have also been altered to chlorite. The decussate texture is clearly evident by the arrangement of recrystallised flakes at various angles to schistosity. The species of chlorite is perhaps rhipidolite, which is feebly

pleochroic with R.I. - β = 1.6267 $\pm$ 0.002. In the garnetiferous rocks the species of chlorite is perhaps 'pennintite' with strong absorption and pleochroism from deep green to light yellow.

Quartz

Quartz generally occurs in the form of lenses, veins, bands and also as isolated grains. Possibly most of this quartz represents introduced silica. The cryptocrystalline variety of silica -- jasperoid and chert -- are also common. They are, however, rare in the barren rocks.

Garnet

Garnet is pale-pink in colour, and sometimes shows anomalous anisotropism probably because of strain effect. It is often fractured and lenticulated and sometimes contains acicular needle-like inclusions of sericite. Often the biotite, chlorite and ore minerals are found in the micro-fractures of the mineral. It is a common mineral in some of the schists associated with ore mineral deposits but in the barren rocks, it does not occur so profusely. Some of the garnets are altered to chlorite and biotite.

Tourmaline

It occurs as aggregates and clots. Sometimes it is arranged in the rock in a radial pattern. The variety of tourmaline is schorlite with pleochroic scheme, E = light brownish white, O = dark bluish grey, (O > E), R.I., N_o = 1.662 $\pm$0.002, N_e = 1.634 $\pm$ 0.002.

Tourmaline is associated typically with the garnetiferous rocks.

Chloritoid

Chloritoid in the form of stumpy needles is interspersed throughout the rock and sometimes shows six-sided euhedral outline. It is distinctly pleochroic from pale greyish green to dull greenish brown (X > Z).

Carbonates

The carbonates are mainly calcite, ankerite and iron-rich dolomite. They are extremely fine-grained and mixed up with sericite and the matrix.

Significant among the other accessory minerals are plagioclase feldspars (oligoclase) occasionally altered to sericite. Talc is very much restricted to the ore-zones and is totally absent in the barren rocks.

Apatite and sphene also occur as important accessory minerals.

Sericitic slates (Plates XV, Fig.2; XVI, Fig.3; XIX, Fig.3).

The sulphide deposits are found in the slates of Daling Series at a number of localities in the area. However, the mineralisation in the Baxa slates is found only at Sikhip. The only difference between the Daling slates and Baxa slates is that of the presence of a high amount of carbonate minerals in the Baxas.

Megascopically, the rocks are very fine-grained, fissile with highly developed slaty cleavage defined by strong preferred orientation of mica and chlorite flakes. The colour of the rocks varies from greyish brown to greenish grey.

These pelitic rocks are essentially composed of mica, chlorite, quartz, feldspar, carbonates, and of accessory minerals like talc, zircon, biotite, etc. The rocks have been highly altered.

Muscovite

Muscovite is very fine-grained, flaky, and highly sericitised. Sericite occurs as colourless to pale green mineral which becomes turbid at places. The amount of sericite becomes so high that the rock becomes 'sericitic'. Some of the flaky porphyroblasts of muscovite show effects of deformation and appear bent. The optical constants of muscovite flakes show a refractive index (Nx) = 1.556 ± 0.002 and $2V_x = 41^\circ$ to 42°.

Chlorite

Chlorite occurs as an ubiquitous mineral in these rocks. Most of the chlorites are derived from biotite. The pleochroic scheme of chlorites shows - x = light green, y = Z = emerald green (Z = Y > X), R.I. - β = 1.628 to 1.630 ± 0.002. The optic sign is found to be characteristically negative in the mineralised zones. These optical characters suggest the species to be 'diabantite' (Winchell and Winchell, 1951).

Quartz

The grain size of quartz varies widely. Where the rocks are highly altered and silicification is prominent the mineral is distinctly coarser. The recrystallisation of quartz is a notable feature. Jasperoid and grey chert are present in considerably high amounts.

Plagioclase feldspar

The feldspars are altered, rare, apparently free from any inclusions and occur as small xenoblasts. They rarely show any lamellar twinning and are optically positive with $2V = 85^{\circ}$ indicating that the mineral is oligoclase.

Accessory minerals

The accessory minerals include talc, iron ores (magnetite and hematite), sulphide ores; zircon in the form of rounded grains, biotite showing a number of leached grains, and some carbonaceous matter. These minerals are characteristically absent or less in the unaltered country-rocks. Talc is predominant among the accessory minerals and it is the diagnostic mineral of the altered rocks. The rock often becomes talcose with the increase in proportion of talc in it. Another important accessory mineral is rutile, which is typically found in the altered zones in clusters. It mostly occurs in association with leached biotite.

The groundmass of the rock is composed of calcite, dolomite and some argillaceous materials.

Quartzites (Plates XV, Fig.1; XVIII, Fig.2).

The quartzites occur interbanded with phyllites and belong to Daling Series. They comprise the wall-rock at several localities in parts of Darjeeling districts. The variety which is more dolomitic belongs to Buxa Series and occurs only at Sikhip.

They are generally medium to fine-grained rocks generally having grey to green colours. Sometimes their colour varies from pink, white to light yellow. Sericitic, dolomitic, silicified and cherty varieties of quartzites were also encountered.

The most common assemblage of minerals in these rocks is quartz, chlorite and muscovite. The accessory minerals include tourmaline, feldspars, zircon, sphene, talc and carbonates.

Quartz

Quartz constitutes about 90% or more of the rock composition. The grain size has an average diameter of 0.24 mm. Quartz veins have profusely intruded the rock along the bedding planes and sometimes across. The presence of jasperoid and chert is a notable feature. Dusty inclusions are found in the large detrital quartz grains.

Chlorite

Chlorite is rarely porphyroblastic. The size of chlorite flakes in these quartzitic rocks is larger than that in phyllites. The optical properties of chlorite correspond to the chlorite of the chlorite-phyllites. Both the species, viz., rumpfite and delessite, have been identified. They are pleochroic from pale yellow to pale green ($X<Y<Z$). The R.I. is found to be - 1.640 to 1.645, and birefringence 0.004 approximately. They are optically positive (rumpfite) as well as negative (delessite). The optically negative varieties are restricted to the mineralized zones, while the optically positive varieties are found in non-mineralized parts of the rocks.

Muscovite

It is mostly sericitic, with an average grain size of 0.015 mm.

Feldspars

They are mainly plagioclase feldspars and are mostly altered to sericite.

Other accessory minerals

Carbonates are rarely present. In One case, they are found to include calcite and dolomite where the latter seems to have been derived from calcitic material by replacement. The differentiation between the calcite and the iron-rich dolomite was made through Otto's etchtest. The presence of talc is a very diagnostic feature showing the possible action of hydrothermal solutions (Lindgren, 1933; Park Jr. and MacDiarmid, 1964). Rutile is characteristically associated in the mineralised wall rocks where the alteration of biotite is dominant.

B. Unaltered country rocks

Petrographic studies of the unaltered country rocks of the area were also made for determining their original characters. The important rocks that are taken into consideration, are slates, phyllites, schists, belonging to the Daling and Baxa Series.

Slates

The slates constitute an important unit in the group of pelitic rocks. Majority of them belong to Daling Series. Only those slates

which are exposed near Sikhip belong to the Baxa Series.

Mineral composition

Muscovite and chlorite are the most important constituents of these rocks. The flakes of these minerals are very tiny and sometimes indistinguishable. Chlorite shows very faint pleochroism. Sericite is rare in these rocks. There are a few very fine-grained quartz. Jasperoid and chert are almost absent. Biotite is a common accessory mineral. Its alteration to chlorite is rare. Sometimes porphyroblasts of biotite are arranged parallel to the rock cleavages. There are a few minute grains of plagioclase feldspar with lamellar twinning. Most of them are unaltered. Among the other minor accessory minerals mention may be made of calcite, zircon and iron ores. Talc is totally absent.

Phyllites

Phyllites are thinly foliated and constitute an important unit of Daling Series. On the basis of their mineral composition the phyllites may be divided into three types, viz., quartz-phyllites, muscovite-phyllites and biotite-phyllites. The textural characters of the various phyllites are similar. These rocks are generally fine-grained and grey to brown in colour. Some are notably porphyroblastic in which the large crystals are oriented parallel to the foliation. Micaceous and chloritic minerals are bent and plicated at places.

Mineral composition

The rocks are composed mainly of quartz, muscovite, biotite and chlorite. The accessory minerals include feldspars, apatite,

tourmaline, chloritoid, iron ores and carbonates. They belong to the chlorite-muscovite sub-facies of the green schist facies.

Schists

They comprise the commonest rock types of this group and belong to the Daling Series. The schistose rocks are well-foliated and fine- to coarse-grained. Away from the thrust zone towards north, numerous quartzose bands occur within the rock. The foliation surfaces in these rocks are very much deformed and puckered. The colour varies from greyish to a silvery white. They may be differentiated into mica-schist, chlorite-schists, etc.

Mineral composition

Quartz is one of the most abundant minerals and found in varying proportions. In the 'mica schists' it does not exceed 20 per cent while in the more 'quartzose varieties' it may sometimes exceed 90 per cent. Jasperoid and chert are totally absent suggesting absence of silicification like that in the mineralized zones. Muscovite is an important constituent of schists and is found in greater amount than biotite. The mineral is flaky and generally arranged parallel to the plane of schistosity. The muscovite flakes are fresh and large-scale alteration to sericite has not been noted as in the case of mineralised wall-rocks. Chlorite is an ubiquitous mineral of these rocks and found in various proportions. Undeformed flakes and needles are common. The mineral is not an alteration product of garnet or biotite as is common in the mineralised wall-rocks. Biotite is generally found in

the form of coarse and recrystallised flakes. It occurs in clusters. Leached grains are totally absent. It alters rarely to chlorite. Garnet commonly occurs as porphyroblasts. The grains are xenomorphic to hypidiomorphic. The grain size rarely exceeds 1 mm in diameter. The colour is usually pink. The alteration of garnet to biotite and chlorite is very rare. Different patterns of inclusion from 'S' shaped (show ball features) to completely rotated trends have been noted in the garnet crystals. Sometimes the rim is totally free and the inclusions are mainly concentrated in the central portions of the crystals. Chloritoid is found to occur as coarse grained idioblasts of prismatic crystals. The prismatic crystals are arranged parallel to the schistosity. Plagioclase feldspars are free from inclusions and occur as xenoblasts. Unlike the case in the mineralised wall-rocks the feldspars in the country rocks are completely unaltered. The important accessory minerals include tourmaline, apatite, epidote and magnetite. Talc is totally absent.

III. Other non-mineralised rock types

Mylonitized schists (Plate XVI, Fig. 2).

The schists are found to occur within a narrow belt of mylonitized rocks all along the sheared zone on the slopes of Rangeng Valley north of Darjeeling. Their maximum thickness is upto 40 m. Petrologically, these rocks are defined as 'biotite-quartz schists', which grade into coarse-grained 'biotite-schists'. They are thinly laminated to coarsely banded rocks which have been refolded, highly

contorted, puckered, badly deformed and crushed.

The rocks are essentially composed of quartz with varying amounts of biotite, muscovite and chlorite. Besides, tourmaline, sodic plagioclases, opaques and apatite are also present. The accessory minerals are usually zoisite and epidote.

Sandstones

The petrography of the Lower Gondwana sandstone has received very little attention, and practically no detailed work has been done. For petrographic purposes, only the two very dominant and type varieties of sandstones were studied. The groups of Gondwana rocks are slightly metamorphosed near their tectonic contacts with Baxa and Daling rocks. The sandstones may broadly be classified into the following two types :

1. Quartzwacke sandstone (Plate XVIII, Fig. 1).

Megascopically, the quartzwacke sandstones are brown to greyish black in colour and poorly sorted with high proportions of argillaceous matrix. The major part of the rock is mainly constituted of quartz and argillaceous matrix. The framework of the rock is predominantly composed of quartz. Undulose extinction of quartz is conspicuous. The matrix is essentially argillaceous. Inclusions of zircon, tourmaline, apatite and the dusty materials occur in the quartz grains. There are a few fragments of plagioclase and potash felspars in addition to some rounded to sub-rounded rock fragments of quartzites, phyllites, slates, cherts, granites and calc-silicates. Zircon, tourmaline, garnet and

iron-oxides are the important accessories. The proportion of matrix is considerably high and composed largely of fine-grained quartz, sericite, chlorite and carbonates. Sometimes specks of iron oxides are disseminated in the matrix. The heavy minerals are zircon, tourmaline, rutile, garnet, epidote, and kyanite. These non-opaque heavy minerals constitute more than 80 per cent of the total heavy mineral assemblage. Besides these coloured minerals, opaques comprising ilmenite, leucoxene and magnetite are also present.

TABLE 3 - Average modal analysis of quartz-wacke sandstone

Minerals	Quartzwacke sandstones (Average of 10 samples)	
	Fresh (% volume)	Altered (% volume)
Quartz	59.00	61.00
Feldspars	3.50	0.50
Rock fragments	3.50	4.00
Matrix	26.00	27.00
Others	8.50	9.00

2. Sub-graywackes

The sub-graywackes form an important lithologic unit and are sometimes slightly metamorphosed. They are usually dark grey to greyish blue coloured and sometimes gritty and coarse-grained rocks. Quartz, albite, feldspars (plagioclases and microcline) and some rock fragments are the usual mineral constituents. The matrix is mainly composed of quartz, sericite, chlorite and carbonate. The plagioclases are mainly albite and oligoclase. The heavy minerals are tourmaline, zircon, rutile, zoisite, magnetite, garnet and actinolite. Several varieties of

quartz may be distinguished. But the most abundant variety is the strain-free quartz.

TABLE 4 - Average modal composition of sub-graywacke sandstone

Minerals	Sub-graywackes (average of 4 samples	
	Fresh (% volume)	Altered (% volume)
Quartz	32.20	19.00
Plagioclase	9.00	10.50
K-Felspars	2.00	0.50
Rock fragments	9.00	22.00
Matrix	40.20	40.00
Others	8.00	8.50

Basic rocks

Some basic rocks occur as sills and dykes in the Daling and Baxa groups of rocks. They are epidiorites, dolerites and metabasites. The petro-mineralogical characters of these rock types have been described briefly as follows :

Epidiorites (Plate XVI, Figs. 4 & 5).

The epidiorites generally occur as sills. They show variation in their colours from dark green to pale green. The rocks are non-foliated and essentially composed of a variety of minerals belonging to the epidote group, in addition to a few amphibole, chlorite, feldspars, iron ores, sphene, calcite, etc. The plagioclase feldspars are altered into saussurite. The original texture of the rock was generally obliterated.

Dolerites (Plate XVII, Fig. 1).

The dloerites generally occur as dykes. Two types of dolerites, viz., 1) unaltered and 2) altered, have been identified.

1. Unaltered dolerites

They are greyish black in colour and medium-grained rocks and composed of plagioclase feldspars, pyroxenes (with their alteration products) and iron oxides. The texture varies from ophitic to subophitic. The marginal portion of the dyke rock is fine-grained with porphyritic texture. While the middle portion is medium-grained. The average diameter of the mineral grains in the fine-grained parts is 0.12 mm, and the average lengths of phenocrysts of plagioclase feldspars and pyroxenes are 1.5 mm and 2.00 mm respectively.

2. Altered dolerites

They are dark grey in colour and medium-grained rocks, composed of plagioclase feldspars, pyroxenes, iron oxides with their alteration products. Sericitization and kaolinization of plagioclase feldspars are common features. Alteration of pyroxenes to chlorite and uralite is occasional. Epidote occurs as discrete grains in these altered rocks. The rocks show sub-ophitic texture.

Metabasites (Plate XVII, Fig. 2).

Megascopically they are green coloured amphibole-bearing rocks of undoubted igneous origin, now completely metamorphosed. They are compact, hard and at places calcareous in nature due to the presence of calcite filled in the vesicles, fractures, etc. The

rocks are generally fine- to medium-grained, and their original textures are obliterated. Nematoblastic texture is sometimes found due to the alignment of fibrous actinolite. When the large actinolite crystals are embedded in a fine and fibrous groundmass of actinolite, then a porphyroblastic texture is observed.

The rock is essentially composed of hornblende, actinolite, sphene, ilmenite-magnetite and calcite. No particular order of abundance of these minerals is found, but in general there is abundance of actinolite with or without albite, epidote and calcite. Chlorite, biotite and plagioclase are found in subordinate amounts.

Granite gneiss (Plate XIX, Figs. 1 & 2).

The granite gneisses, belonging to the Darjeeling Series and forming the suite of older granite rocks are medium- to coarse-grained foliated rocks. The biotite-gneiss, garnetiferous biotite-muscovite gneiss, and the sillamanite-biotite gneiss are the prominent varieties. The important mineral constituents in the order of decreasing abundance are quartz, feldspars (potash feldspars predominating), biotite, garnet, muscovite, sillimanite, epidote, hornblende and opaque minerals.

A brief mineralogy of the various essential and minor accessory minerals is given as follows :

Quartz

Quartz occurs as large and small, fractured and unfractured crystals sometimes with chlorite and mica swerving around it. It is colourless, weakly birefringent and having wavy extinction. Elongated,

recrystallised crystals with crenulated margins occur parallel to the foliation. It is also found in the micro-fractures of plagioclase feldspars.

Feldspars

a) Potash feldspars - Microcline and perthite are the chief feldspars.

Anhedral crystals of microcline with characteristic cross-hatched twining and extinction angle are seen to be crowded with inclusions similar to that of the groundmass. It encloses quarts and other feldspar grains partially along the borders. In a few cases the phenocrysts are of microperthites. The microcline-microperthite contact is indistinct. The perthite lamellae are irregular and sometimes anastomosing lenticular masses occur usually in optical continuity. Islands of quartz occur in optical continuity with perthites. The boundary between plagioclase and microcline is invariably irregular as apophyses of each mineral penetrate along the contact.

b) Plagioclase feldspars

Plagioclase feldspars are less abundant than the potash feldspars. lath-shaped crystals are common in which the extinction angle ranges between 0° and 18° indicating thereby an albite-oligoclase composition. Clouding of plagioclase is very common.

Biotite and muscovite

Biotite is strongly pleochroic from very deep greenish brown to pale brown and sometimes it is enclosed in plagioclase. The flakes

are oriented parallel to the foliation. Pleochroic halos are common. Minute inclusions of zircon with pleochroic halos are also seen. Biotite predominates over muscovite, which occurs in the form of small crystals of flaky habit. Muscovite is sprinkled with tiny dust like particles.

Other minerals

Some of gneisses have hornblende showing the usual pleochrism and orientation parallel to the rock foliation.

Sillimanite is abundantly developed in some gneisses which exhibit fibroblastic textures. Garnet occurs as colourless rounded grains, generally surrounded by biotite flakes. The S-shaped inclusions of quartz is a positive evidence of rotation of garnet.

Epidote crystals are equidimensional and highly pleochroic from yellow to yellowish green colour. Two varieties of epidote have been identified:

a) Clinozoisite - Colourless and biaxial (- ve).
b) Pistasite - Pleochroic and with high order interference colours.

Minor accessories

Among the minor accessory minerals mention may be made of zircon, tourmaline, sphene, cordierite, staurolite, etc. which have also been identified by their respective optical characters.

Opaque minerals

They mostly include magnetite and haematite.

Lamprophyres (Plate XIV; Fig 2).

Lamprophyres are usually highly altered to chlorite-calcite

rock. In fresh outcrops typical lamprophyric texture and mineralogy is, however, well preserved. The rocks are melanocratic and frequently show the typical porphyritic texture.

Microscopically, the rocks are medium- to fine-grained and/prophyritic with panidiomorphic groundmass texture. The lamprophyre is of vogesite (?) type.

Mineral composition

Green hornblende is fine-grained and composes largely the groundmass of the rock. Aegirine-augite is the common variety of pyroxene which occurs only as phenocrysts. Plagioclase and orthoclase are the common feldspars. The groundmass as well as the phenocrysts are composed of plagioclases. Orthoclase is found only in the groundmass.

Read Carefully 16.11.77

METAMORPHISM

The two rock series, namely the Dalings and the Darjeelings, have essentially been affected by regional metamorphism associated with tectonic movements in the Himalayas during the Tertiary times. Contact metamorphism in these rocks, which is unrelated to any tectonic disturbance, is conspicuous only around the larger bodies of igneous intrusives or within the zones of intense hydrothermal activity which caused the deposition of copper and lead-zinc sulphides.

The progressively increasing regional metamorphism of the epi-metamorphic slates through meso-schists of the Daling Series into kata-metamorphic Darjeeling gneisses is a classic example of reverse metamorphism in the Himalayas. It has been observed by many of the

previous workers as well as present author that the reversal of metamorphism with lower grade Daling slates, phyllites, schists, etc. occupying the lower horizons and the higher grade Darjeeling gneisses overlying the Dalings, is a consequence of inversion of the sequence due to the overturning of a recumbent fold.

The chemical study of the rocks belonging to Darjeeling and Daling Series have revealed that they represent different facies of one continuous sedimentary sequence. The gradual and steady increase in SiO_2 content and decrease in Al_2O_3 content from the Daling slate to Darjeeling gneiss (Table 5) are indicative of a regular lithologic variation of the set of metamorphic rock series. The preponderance of soda over potash and their gradual decrease in weight per cent from slate through phyllite and schist to gneiss is an important evidence of their common derivation from an essentially argillaceous sediment. The most significant chemical features of all these rocks is a very restricted variation of TiO_2. This is possible only when the source materials of all these rocks are common. CaO/MgO ratio systematically decreases from the lower to higher grade rocks. P_2O_5 shows a regularly decreasing trend from slates to gneisses in which it becomes almost insignificant. FeO/Fe_2O_3 ratio has a more or less similar value in the slate and gneiss but it shows slightly higher values in phyllites and schists. Auden (1935) and Heim and Gansser (1939) have also given similar views, and believe that the rocks belonging to Darjeeling and Daling Series are dominantly argillaceous in bulk composition. The spatial distribution of the index minerals like chlorite, biotite, garnet, kyanite and sillimanite in the

TABLE - 5 Chemical composition of rocks belonging to Daling and Darjeeling Series

Major Elements	Darjeeling granite-gneiss Wt. per cent (Average of 8 samples)	Daling schist Wt. per cent (Average of 10 samples)	Daling phyllite Wt. per cent (Average of 9 samples)	Daling slate Wt. per cent (Average of 7 samples)
SiO_2	63.64	44.72	40.20	38.60
TiO_2	2.10	2.81	2.20	3.00
Al_2O_3	17.91	24.40	26.20	28.65
MgO	1.10	1.62	2.20	3.20
Fe_2O_3	2.87	3.04	5.10	3.12
FeO	2.39	4.0	6.30	3.20
CaO	0.68	2.58	3.80	8.55
MnO	0.09	0.03	NF	0.10
Na_2O	3.6	3.78	5.80	6.36
P_2O_5	0.08	1.13	2.08	2.92
K_2O	2.95	5.44	3.30	1.60
H_2O^+	2.00	5.43	1.40	0.41
H_2O^-	0.16	0.19	0.25	0.31

N.F. = Not Found

two rock series in Darjeeling and Kalimpong areas indicate that their progressive regional metamorphism has the same features as those described by Barrow in the Scottish Highlands (Ray, 1947). In the metamorphic facies map of Ray (1947), which also covered a part of the present area, the zones corresponding to the index minerals chlorite, biotite, garnet and kyanite in the Daling series and sillimanite in the Darjeeling Series are quite distinct. The author came across such distribution zones of index minerals not only in the eastern and western sides of the Tista valley but also in the regions lying north of Darjeeling. Gansser (1964) has also observed similar metamorphic facies distribution in this area.

It may now be finally stated that the original constituents of all these rocks were essentially pelitic, probably shales, which were subjected to regional metamorphism varying from low grade green schist facies to high grade kyanite-sillimanite facies. The Daling quartzites and the Baxa limestones which were also involved in this metamorphic episode probably correspond to the arenaceous and calcareous facies of the original sedimentary sequence. A clearer picture of the mutual relation between the lithological units in different zones of metamorphism and the probable source rock is presented in the table (6).

TABLE - 6 Probable source rock and corresponding lithological units in different metamorphic zones in Darjeeling and Daling Series

Original rock	ZONES				
	Chlorite	Biotite	Garnet	Sillimanite	Feldspar
	Daling Series			Darjeeling Series	
Shale	Slate	Clay phyllite	Garnet-biotite phyllite/ schist	Sillimanite gneiss	Porphyro-blastic gneiss
Arenaceous shale	Phyllite		Garnetiferous mica schist	-	-
Quartz sandstone	Quartzites				

Chapter IV

STRUCTURAL SET-UP OF THE AREA

General statement

An attempt is made here to present the general structural pattern of the area. The results of the investigation are based on the structural data, collected in the field and indicated on the geological maps (Figs. 1 & 2). Some of the structural characters of minor importance related to the various litho-stratigraphic units have already been dealt in the earlier chapter on the 'Stratigraphy and Lithology'.

In the Darjeeling Himalayas, the major tectonic trend is E-W. It is much in harmony with the general trend of the eastern Himalayas. The E-W as well as N-S trending structures in the study area are largely controlled by the major fold and fault systems such as Tista valley and Ranjit valley anticline, Darjeeling and Algarah synclines, the Main Boundary Fault, Daling thrust, the Gondwana tectonic window, etc. (Figs. 13 & 14). The trend of the older plutonics (granites) is E-W and N-S, and that of the younger plutonics (granites) is NW-SE and NE-SW.

Smaller structural features such as minor folds, faults, foliations, slickensides, boudinages, joints, etc., which are quite

INDEX STRUCTURAL MAP OF DARJEELING
AND KALIMPONG AREAS

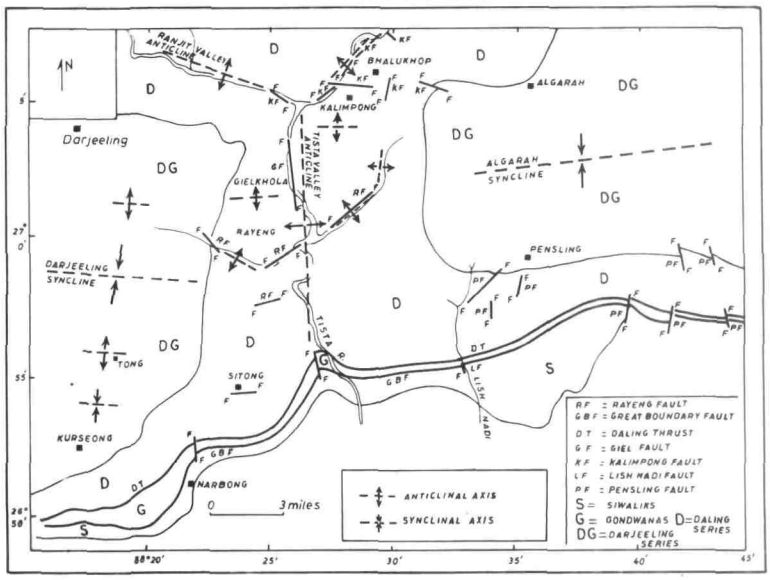


Fig.13

INDEX STRUCTURAL MAP OF THE AREA
AROUND RISHI AND PEKU

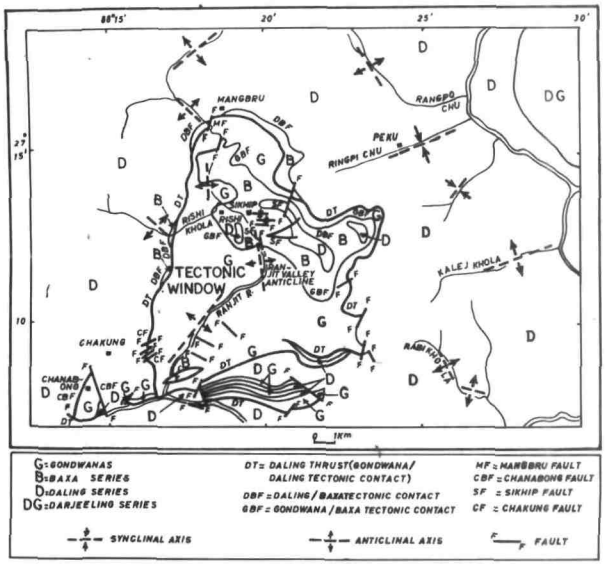


Fig.14

common and conspicuous in the area, have also been recorded in large numbers. But it was not possible to present them here in much detail in the general survey of the structures.

The major structural deformation of the area was largely due to the Tertiary Himalayan orogeny that was spread over into four phases from the early Eocene to late Pliocene times. Age determinations by lead isotope methods indicate that the younger plutonics (granites) were emplaced during the late Miocene times, and the older one, in the Pre-Cambrian. There is ample evidence to believe that base metal and radioactive mineralisations are of tertiary age and occurred after the intrusion of the younger granites.

Although the majority of the rock-formations of the area have been deformed as a result of such orogenic movements during the upheaval of the Himalayas in the tertiary times yet the imprints of tectonic disturbances are faithfully preserved in them. The intricate system of folds, faults, thrusts and other minor structures broadly indicate that the tectonic pattern of the area is much more complex than elsewhere in other parts of the Himalayas. But in spite of this tectonic complexity, the rocks show a general paucity of penetrative structures when considered on mesoscopic scales. The following structural features are commonly associated with the rocks belonging to the Darjeeling, Daling and Baxa series, Gondwana and the Siwaliks.

I. Minor Structures

A. Folds with associated Planar Structures

Various types of minor folds are quite common in the area. They range in length from 5m down to less than 2 cm and occur frequently in the sedimentary and metasedimentary rocks. These folds with associated planar structures have been classified into three categories belonging to three different generations and the descriptions of which are given as below:

1. First Generation Folds (F_1)

The first generation folds (F_1) are greatly compressed, long-limbed, near isoclinal, with very steep plunge. The folds are mostly doubly plunging, asymmetric and similar. The fold dihedral angle does not exceed 35°. The axial trend of the first generation folds (F_1) varies from NE-SW to ENE-WSW.

The schistosity of the foliated rocks is of axial plane type and disposed at low angles to the lithologic bandings. It is defined by the parallelism of feldspars, micas and quartz.

The initial orientation of these folds is partly disturbed by the second and third generations of folds (F_2 and F_3). Near the hinges of the larger F_2 folds they are recumbent or nearly so, while in the limbs, they are near-recumbent to steeply inclined. The wide variation in the geometry of these folds is mainly due to refolding during later movements.

2. Second Generation folds (F_2)

These folds are the most conspicuous structural features of the area. They are doubly plunging and developed on all scales from minute puckers to large macroscopic folds. The general trend of these folds is NW-SE, and sometimes NNW-SSE. The axial planes are sub-vertical to moderately inclined. An overturning towards the south is sometimes conspicuous. These folds are generally found to be more open than the previous ones. An axial plane cleavage is often associated with these folds.

The orientation of this generation of folds is also affected considerably due to later folding.

3. Third Generation folds (F_3)

These folds are also doubly plunging and generally have NE-SW to E-W trending axes. They were superposed on F_1 and F_2 folds. The pattern of folding shows considerable variation from place to place. Most of them are symmetrical, upright or inclined. Sometimes they are found to be disharmonic. This folding is also parallel because the folded layers generally maintain a constant thickness. Sometimes an axial plane cleavage is developed.

B. Joints

The diastrophic joints are very well-developed structural features. They are often closely spaced, straight and show little deviation in the successive beds. The competency, thickness and the position of the folds are the main factors controlling the

jointing. Joints in the case of phyllites are very well-developed and closely spaced. The quartzites and limestones are also highly jointed. The following three types of joints have been recognised:-

1. Strike Joints

The trend of the strike joints is variable. However, the prominent sets have E-W and ESE-WNW strikes with dip angles of 55° to 90° towards north as well as south.

2. Cross Joints

The cross or 'ac' joints are developed almost at right angles to the strike joints. It is the most widespread joint system in the area. The strike of one of the most frequently occurring sets is from north to south.

3. Oblique Joints

Generally two prominent sets of oblique joints are found. One of the sets strikes from N 15°W to N 55°W and dips towards NE or SW at angles varying between 30° and 75°. The strike trend of the other set varies from N 25°E to N 55°E. The dip angles vary from 40° to 85° towards SE or NW. At many places, these two sets of joints intersect each other at high angles.

The strike frequency of the joints from different parts of the area have been plotted in rose diagrams (Fig. 15). Strike joints are generally less prominent than the other types of joints. The cross joints constribute to the major joint system in the area with a

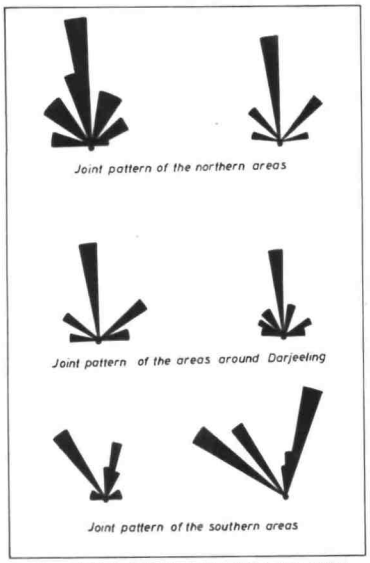


FIG. STRIKE-FREQUENCY DIAGRAMS FOR JOINTS OF THE AREA AROUND DARJEELING HIMALAYAS

Fig. 15

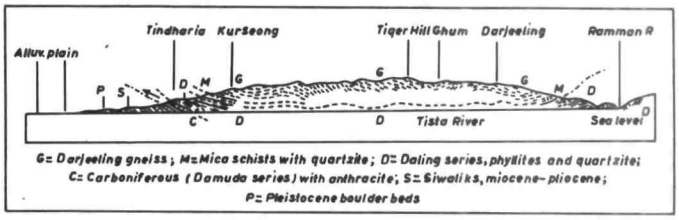


FIG. SECTION ACROSS DARJEELING HILL
(after: Heim and Gansser 1939)

Fig.16

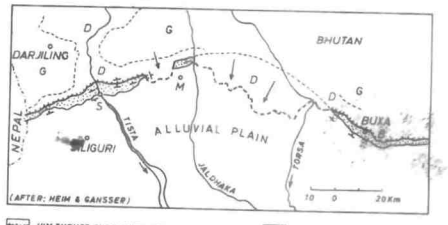


Fig.17

SKETCH-MAP OF THE HIMALAYAN ADVANCES THROUGH THE SIWALIK GAP EAST OF THE TISTA. G= GNEISS; D= DALING SERIES; IN THE WESTERN PART INCLUDING DAMUDAS (CARBONIFEROUS); B= BAXA SERIES; S=SINGH RAILWAY STATION; M= MATIALI.

Fig.

N-S trend. Oblique joints are also well-developed and common in the area. They are particularly prominent in the southern part of the area.

C. Slickensides

Slickensides occur in most of the competent rocks like quartzites, limestones, dolomites and also in granites. Some of the slickensides, plunging 30° to 45° towards SSW to SW, may be related to the thrust movements. The attitudes of slickensides associated with the fault movements are 35°, N 30°E; 40°, S 10°E and 45°, N 5°W.

D. Boudinage structure

Boudinage structure is very common in the phyllites. It is characterised by parallel and elongated disc or sausage like bodies of quartzite or vein quartz in which pinch-and-swell structures are well-developed. At some places near the thrust zones the boudinage structures in the phyllites strike almost at right angles to the minor folds.

II. Major Structures

A. Major folds and thrusts

The present knowledge of the structure of the study area is partly based on the excellent work done by Mallet (1875), Von Loczy (1907), Wager (1934), Auden (1935), Heim and Gansser (1939) and Ghosh (1951, 1956). The first attempt to apply the nappe theory in

the Himalayas was made by Von Loczy (1887) who during a lecture at the Hungarian Geological Society postulated an enormous recumbent nappe like fold with the Darjeeling gneiss overlying the younger beds for over 25 km distance in the eastern Himalayas. Heim and Gansser (1939) stated that, "the Darjeeling gneiss and its continuations in the Kangchenjunga massif belong to a large recumbent anticline thrust from N to S over a wide surface of more than 80 km, while the Darjeeling gneiss is underlain and surrounded by younger sedimentaries, the huge Kangchenjunga massif represents the root zone of the great Darjeeling thrust folds" (Fig. 16). They (1939) also observed that the core of this recumbent fold was spread over the Sikkim and Darjeeling Himalayas and composed mostly of Darjeeling gneiss. Later Ghosh (1951, 1956), observing the behaviour of the isograds in the Daling rocks, the occurrence of unmetamorphosed marine Permo-Carboniferous rocks in a window north of Darjeeling concluded that the Daling sequence might be forming an inverted limb of a gigantic recumbent fold which was quoted as "the largest known thrust fold of our globe". The stratigraphic position of the Darjeeling series below the Daling series with a gradational zone of garnetiferous mica schist between the two in the Kangchenjunga massif was considered to be normal by Hallet (1875), Suess (1885, 1901), Von Loczy (1907), Wager (1934) and Auden (1935). Here the metamorphic grade of the rocks increases gradually from the top to the bottom of the formation. The Dalings are overlain by the Lachi Series and other younger formations of Permo-Carboniferous to Jurassic age.

A critical study of the work area, where both the Darjeeling and Daling Series occur, indicates that the sequence has been reversed probably due to overturning of the recumbent fold and consequently the Darjeeling gneiss overlies the younger Daling Series. The metamorphic grade of such an inverted sequence is, therefore, expected to be in reversed order. Evidence of such a reverse order of metamorphic grade was observed in the Tista valley as well as near Kalimpong, where the lower slates and clay phyllites pass upwards into gneisses through various metamorphic rocks of intermediate grade. The study area thus, has an unusual order of metamorphism, due to inversion of the Darjeeling and Daling series due to intense tectonic disturbance. There is a gradational contact zone, composed of garnetiferous mica-schists between the two rock series. Wager's (1934) view of a thrust between the Darjeeling gneiss and the Dalings is, therefore, not tenable. Ray (1947) also ruled out the previous idea of thrusted contact between the two rock series due to the absence of any cataclastic structures and any discordance in the progression of metamorphism. However, there are indications of faulting of a local nature at the contact between the Dalings and Darjeeling gneisses in some of the sections, such as north of Darjeeling (Hallet, 1874). Such localized fault zones have been found at various other localities in the Tista valley, the Gayabari area near Algarah and Risaum. Auden (1935) accepted the possibility of the existence of local thrusts within the Darjeeling gneiss-Daling Series sequence, which may be of small horizontal displacement.

1. Siwalik/Gondwana boundary (Great Boundary Fault)

The existence of a thrust fault has sometimes been presumed to explain an anomalous relation between stratigraphic units, and such a relation exists between the Siwalik and Gondwana Systems in the area under study. The Gondwanas are represented here by Damuda Series. In fact, there are important indications of intense deformations and great movements related to this thrust fault and hence, it is considered to be a major structural feature.

This thrust is a part of what is known as the 'Great Boundary Fault', which continues along the entire stretch of the Himalayas separating the Siwaliks from the pre-tertiary rocks. It is actually a series of 'reversed thrust faults'. The junction between the rock groups is generally masked by rock wastes due to which the tectonic contact has been obscured.

Siwalik Gaps

The gaps in the Siwaliks east of Tista river (Fig. 17), where the Tertiaries are wanting for a few miles are very conspicuous. The Siwalik front range east of Tista ends abruptly without changing its regular ENE strike and northerly dip directions, whereas the strike of the pre-tertiary rocks is bent here at right angles to the former. Heim and Ganser (1939) attempted to correlate the Siwalik gaps with similar gaps in the Alps of Western Switzerland.

2. Daling/Damuda Boundary (Daling Thrust)

The Siwaliks, forming the frontal range of the Himalayas, are

in normal position. The Damudas on the north rest against the Siwaliks with a thrusted contact and so is the case with the Daling Series, which was thrusted over the Damudas. The tectonic set-up of these three formations are shown as below :-

Darjeeling Series		(High Ranges)
———————	Predominently a gradational zone	
Daling Series		
- - - - - - - - - - - -	Daling Thrust	(Between the foothills and the high ranges)
Damudas Series		
- - - - - - - - - - - -	Main Boundary Fault	
Siwalik System		(Foothills)

It was essentially these thrust faults that have caused many vagaries in the normal strike of the rocks and of folds in this portion of the eastern Himalayas. Due to the Daling thrust, the Damudas suffered a sudden change in their dip direction from NNW to NNE between the 17th and 18th milestones by the side of the Tista river. Drag folds and brecciation are common not only here but also at several other places like Nana Khola, Rakti Khola, Parbujhora, Lish Nadi sections, Mahanadi section, Gish nadi section, Tindharia, etc. where the boundary thrust is easily discernible. This thrust is traceable from Tindharia area, in the southeastern part of Darjeeling, to north of Darjeeling near Jhum, Rangbong, Nayabazar, Mongyong and Mangbru. The structure is apparently that of a folded thrust (Figs.1 & 2).

Tectonic window

The Gondwanas are exposed in a tectonic window in the northern part of the study area obviously due to profound erosion of the overlying Dalings along the Ranjit river valley (Fig. 14). The Baxas are also exposed within the window. The Gondwana rocks are surrounded by the overlying Daling Series.

3. Daling/Baxas and Gondwanas/Baxas boundaries

The contacts between Dalings/Baxas and Gondwanas/Baxas are of tectonic nature. Drag folds and puckers are extensively developed. The rocks on either sides of these tectonic contacts maintain the same structural trend.

B. Other faults

There are many other faults in the area. But only the major faults, which extend from several hundred to several miles in length, have been recorded on the maps (Figs. 13 and 14). Generally speaking, they have been recognised where the stratigraphic and structural discontinuities are conspicuous with occasional indications of slickensiding, brecciation and silicification. Fault valleys, and other topographical expressions like fault-scarps have also been helpful in this respect. Most of the faults are reverse and strike either longitudinal or transverse to the strike trends of the affected rocks.

1. Giel fault

This is one of the major faults, the alignment of which is

coincident with the axial region of a major N-S trending anticline in the Daling Series. This also happens to be the course of the Tista river valley (Figs. 1 & 13).

2. Kalimpong

A set of faults has been recorded from the north of Kalimpong and the east of Bhalukhop. Their strike trends are E-W and WNW-ESE. They control the courses of the Tista river and its tributary, Bhalukhop Khola. A prominent fault scarp is exposed all along the faulted course of the Tista river.

3. Rayeng

A number of faults have been recorded from around Rayeng where they show prominent displacements in the Dalings and also in the Darjeeling gneiss. The NE-SW, NW-SE and N-S trending faults present a radial pattern. Some of them, which occur along the axial regions of major anticlines, have controlled the courses of certain streams.

4. Lish Nadi

Here the trend of the fault is roughly parallel to Lish nadi, and it has displaced only the southern boundary of the Damudas. The northern boundary was not affected.

5. Pensling

A number of important and more conspicuous faults have been recorded in the areas lying east and southeast of Pensling, and also in the neighbourhood of Nebong. These faults are almost parallel to

one another and strike have NE-SW or NNW-SSE strikes. The faulting along the Gish nala and a parallel set of faults east of it have created a gap in the Siwaliks. It is due to this set of faults that the pre-Tertiary rocks (including Gondwanas and Dalings) were displaced southwards.

6. Sikhip

Two important faults run N-S and NW-SE along the axial regions of two major folds which cross each other and plunge due north and northwest respectively (Fig. 14). The NW-SE trending fault forms a prominent fault scarp at Sikhip. The other N-S trending fault follows the course of the Tista river. South of Sikhip there are two faults which intersect one another and form a V-shaped pattern (Figs. 2 & 8). One of the faults trend E-W and the other one, NE-SW.

7. Chanobong

The fault at Chanobong has displaced the thrusted contact between the Dalings and Damudas. As a result of this the rock formations on either sides of the fault have been drag-folded (Fig. 2). A fault scarp is prominent here.

8. Chakung

A set of four parallel faults displacing the Damuda and Daling boundary and two other parallel faults in the Gondwanas have been recorded from the east of Chakung (Figs.2&13). The Damuda coals near the faulted contact are graphitic and highly pulverised.

9. Mangbru

A fault south of Mangbru runs N-S and it has also displaced the thrusted contact between Dalings and Damudas (Fig.). On meeting this fault at Mangbru in the downstream, the Ranjit river takes a sharp turn towards east from its original N-S upstream trend. Two other faults, that occur a little further south, have N-S and E-W trends (Figs. 2 and 14).

10. Pachikhani

A set of two intersecting faults occur near Pachikhani. One of the faults, which trends N-S, controls the course of Pachi Chu and the other fault running E-W controls the Rangli Chu (Fig. 5). Here also the fault scarps are prominent.

11. Chuzakhan

South of Chuzakhan, there is an E-W trending fault which has caused prominent displacements of geological formations. The Rangli Chu bends sharply towards the west at a place where it meets the fault, south of Chuzakhan (Fig. 5).

12. Simana

A fault, trending NE-SW near Simana, also caused prominent horizontal displacement of the rock outcrops. It terminates against another fault, running ESE-WNW, along which the Rache Chu flows. The axial plane trace of an anticline plunges due WNW and the fault almost coincides with it.

13. Rangpo

There are three prominent faults near Rangpo. Their NNW-SSE, E-W and ESE-WNW trends have controlled the directions of the Tista river, Rangpo Chu and Rongni Chu respectively. Fault scarps, crushed and brecciated zones, and displacements of geological formations are conspicuous all along these faults (Fig. 18).

C. Major folds

1. Regional

The major folds are asymmetrical and mostly overturned towards the south. Recumbent folding, overturning of the folds and other evidences of intense tectonic movements have been recorded. Gansser (1964) believes that the rocks display "a regional south vergent tectonic style with north-east directed fold axes". Invariably the valleys in the Daling Series are anticlinal and the pitch of the anticlines is northwards. On the other hand the prominent hills are formed in the synclinal portions of the Darjeeling gneiss.

a. Tista valley anticline

The general dip direction of the Daling rocks in Darjeeling area is always towards the hills, i.e., northwesterly in the south; between westerly and northwesterly in the Tista valley and the eastern slopes of the Takdah, Rangpu hill; easterly on the western slopes of the Kalimpong hills. The dip angle of the fold limbs generally varies from 30° to 50° (Figs. 1 and 13).

b. Rangit Valley Anticline

In the Ranjit valley the strike of the Dalings swings from NW-SE to NE-SW direction from east to west, with consistent north-easterly and northwesterly dips respectively. This marks a broad anticlinal warp in these rocks with respect to the N-S axis (Figs.2 & 14).

c. Recumbent Folding

At many places the sequence of Daling Series is inverted. This position of the Dalings is due to the overturning of a major thrusted recumbent fold with its axis oriented E-W. This recumbent anticlinal thrust is a part of the large fold thrust that extends for a distance of about 80 km from the Darjeeling Himalayas to the Kanchanjunga (Karunakaran, 1964). The occasional normal sequence of the beds in this terrain may be due to digitations and refolding of the limb. Due to overturning, some of the rocks of the recumbent fold have overidden a significant portion of the Gondwana sequence. The occurrence of dolomite belonging to the Baxa Series at different tectonic and stratigraphic positions may perhaps be due to the fact that concomitant to overriding of the Dalings, some portions of Baxas, which constitute the upper part of the Dalings, have been severed off and moved to their present positions. The Baxa limestones and the Gondwana rocks in the tectonic window are folded together repeatedly into isoclinal synforms and antiforms plunging at 20°-35° towards northwest.

d. Folding in Siwaliks and Damudas

Siwaliks and Damudas form a major anticlinal structure with

its fold axis trending E-W to ENE-WNW.

e. Darjeeling Synclinorium

The gneissic rocks belonging to Darjeeling series form a synclinorium from north of Tindharia near Kurseong to the north of Darjeeling upto the slopes leading to Ramman river valley. The strike trend of the synclinorium is ESE-WNW. The secondary folds within the syncline indicate that the plunge ranges from 10^{0} to 20^{0} due west. Three synclinal structures that occur near Kurseong, Ghum and Darjeeling form the Darjeeling synclinorium and on which stands the Darjeeling town, including the highest Tiger Hill.

f. Algarah Syncline

The gneissic rocks that occur south of Algarah town also form several synclinal hills covering a large area. The plunge of the ENE-WSW and NE-SW trending synclines varies from 10^{0} to 20^{0} due west.

2. Other important fold structures

a. A beautiful overturned syncline pitching 15^{0} due NE is exposed in a section 3 km SE of Kurseong on the Darjeeling road. This structure perhaps belongs to the reversed frontal part of the great thrust fold.

b. Rayeng anticlines

The trends of two anticlinal folds in the Dalings that occur near Rayeng, on the eastern and western sides of Tista river, are NE-SW and NW-SE respectively.

c. Kalimpong anticline

The Daling series forms an anticline south-west of Kalimpong, on the eastern side of Tista river. The anticline trends in an E-W direction and plunges 20° due East.

d. Rabi anticline

The course of the Rabi Khola follows the axial region of an anticline in the Daling rocks trending NW-SE and plunging 25° due NW. Similarly, Kalej Chu and Rangpo Chu pass through the axial regions of another two anticlines trending ENE-WSW and NW-SE respectively. These anticlines plunge due ENE and NW respectively.

e. Sikhip folds

Two doubly plunging folds occur in the Baxa rocks on the eastern side of Ranjit river near Sikhip. The axial trend of these parallely disposed folded structures, which include an anticline and a syncline, is NW-SE, and their pitch is towards northwest (Fig. 8).

Chapter V

NATURE AND MODE OF OCCURRENCE OF SULPHIDE ORE DEPOSITS

Introduction

There is a widespread occurrence of sulphide ores in the Darjeeling Himalayas covering parts of Sikkim, and Darjeeling district of West Bengal. Copper and lead-zinc ores occur sporadically in the Baxa and Daling group of rocks. There are some ancient copper and lead workings in the area, which date back to one hundred years or more. Most of them were abandoned long ago due to economic reasons. All the copper ore deposits of the area are confined to the Daling Series. Some lead ores occur mainly in the carbonate rocks of the Baxa series, and to a limited extent in the Daling Series.

Types of deposit

The sulphide ore deposits have been classified into the following three types, based on their morphological features which have also some genetic significance.

Vein and stringer ore
Disseminated ore
Massive ore

In addition to these, irregular and minor replacement ore bodies also occur. The mineralisation is both of 'replacement' and

'open-space filling' type.

Vein and stringer ore

The ore-bearing veins and stringers are most common in the area. The walls of the mineralized veins and fissures are sometimes filled up with crustified vein matter. Quartz in the vein is commonly arranged in a comb structure towards the central part of vug. Such types of mineral veins are said to be strictly confined to shallow depth or surface area (Stillwell, 1918; Chace, 1949; Howe, 1924; Dougherty, 1925; Ferguson et al., 1932; McKinstry and Noble, 1932 and McKinstry, 1955).

Fine to thick ramifying or braided veins cut across the more silicified chloritic, sericitic, biotitic and schistose rocks. In most of the cases the veins and stringers have well-defined walls and distinct contacts with the country-rocks. It is only in the extremely crushed zone that the nests and reticulate veinlets of sulphide ores are common.

In general, for the purpose of present study, the veins and stringers may be regarded as tabular bodies of mineralized matter localized in the zone of fractures regardless of whether the vein matter was introduced by filling, by replacement or by a combination of the two processes.

The mineralized veins are easily distinguished if they cut across the foliation or the bedding planes of the country-rocks.

Sometimes these tabular bodies are so localised that they partly follow the bedding direction of the country rocks and partly cut across them elsewhere. In some of other cases, the veins also follow the rock foliation.

Disseminated ores

Very minute and small specks of ore, which are sparsely distributed in the rocks or occur along closely spaced fractures within a larger volume of rock are described here as disseminated ore. The disseminated ore is largely confined to the highly altered, granular and quartzose rocks. The mineralization is ideally localized in the highly silicified and quartzose rocks in the form of minute blebs, filling the intergranular spaces between the quartz grains or replacing their constituent minerals like chlorites, sericite, biotite, carbonates, etc. Where the disseminations are closely spaced, the blebs sometimes coalesce and thus their "seed-like" shape is transformed into a mesh of small scale veins. The opaque minerals are essentially composed of chalcopyrite, pyrite/marcasite, galena with a few other associated minerals.

Massive ore

The term massive ore is used in this report in lieu of a better designation for the ore 'solids' or 'bodies' emplaced in open or widely gaping fractured zones of the brecciated vein-quartz which is confined typically to the sheared horizons. Mineralogically, such ore bodies are composed of chalcopyrite, pyrite, galena and a few other associated

minerals. The general shape of massive ore in the sheared zones sometimes varies from sub-rounded to elliptical form. Proportions of gangue minerals vary from one ore-body to the other.

Occurences of sulphide ore deposits

The important sulphide ore occurrences have been mapped in detail with the help of plane table in order to investigate the local form and distribution of the ore deposits and their possible controlling factors.

I. Lead-zinc Deposits

Rishi area

About 2 km north of Rishi Bazar in West Sikkim, deposits of galena with occasional specks of sphalerite occur in the form of impersistent lodes within the dolomitic limestones and dolomites belonging to the Daxa Series, which is exposed on a ridge overlooking the Ranjit river on the west (Fig. 9). The Pb-Zn lodes are localised along shear planes, and diagonal joints and to a lesser extent along the bedding and the sub-parallel foliation planes of the country rocks. The mineralisation is localised in the following two within a vertical distance of 300 m (Figs. 6 and 7):-

A. Upper mineralized zone

The uppermost zone (Fig. 7) is situated at an altitude of 900 m above m.s.l. The galena lodes are lensoid in shape and impersistent laterally. The maximum thickness of a lode is nearly 8 cm. Sometimes the thickness is considerably reduced by lateral splitting.

The lodes are rich near their central portions but they become lean near their contact with the country rocks. On the whole, the lodes contain a fair concentration of galena with subordinate amounts of sphalerite and pyrite. The minor offsets in the mineralized zone (Fig. 7) are due to some post-mineralization faults.

The dolomitic limestones are intricately traversed by two generations of quartz-calcite veins. The first generation veins are comparatively more coarse-grained and contain more calcite than the second one. Galena is invariably associated with the first generation of veins. It is apparent from the contour diagrams (Fig. 7) of the quartz-calcite veins of the first generation that they are mostly diagonal to the bedding strip of the dolomitic rocks, and that the majority of them have a northeasterly dip at high angles. There is also a concentration of the poles of the lodes in the maxima of the quartz-calcite veins. These are guided by a minor set of diagonal joints. On the contrary, the quartz-calcite veins of second generation are mostly normal to the bedding strike and are apparently guided by a set of cross joints.

There are a few thin galena veins (2-3 cm in thickness) which are disposed parallel or sub-parallel to the bedding striking N 20°-35°E and dipping 60°-70° in a northwesterly direction. Some stringers of galena often show stockwork types of ramifications within the country-rocks. The most favourable host rock for Pb-Zn ores in this area appears to be the siliceous dolomites and dolomitic limestones.

B. Lower mineralized zone

The lower mineralized zone (Fig. 6) is situated at an altitude

of 550 m above m.s.l. and aligned approximately on the strike continuation of the dolomitic rocks in the upper zone. The country rocks are the same as in the upper zone but they are interbanded with calcareous phyllites. Galena with some sphalerite and pyrite is either localized in the quartz-calcite veins or occurs along the shear planes in dolomites, dolomitic limestones and calcareous phyllites (Fig. 6). The shear planes are mostly bedding plane shear type, but occasionally they cut across the bedding at acute angles. These mineralized shear planes are often wavy in shape and frequently bifurcated. There is a major shear plane which extends over a distance of 45 m in NE-SW direction. This shear plane has mineralization of Pb-Zn at several places. Near the middle range of this mineralized shear plane,another smaller shear plane, sub-parallel to the former, was located. These two are connected together with another shear plane which is also mineralized. It is, therefore, evident that the intersection of the shear planes has served as a favourable structure for controlling the localization of the Pb-Zn deposits in this area. The nature of the ore in the brecciated zone is generally massive but elsewhere it is mostly of the vein and stringer type. Although the shear planes are fairly continuous and well-defined, yet the mineralisation is sporadic and the mineral veins pinch and swell. The maximum thickness of an individual vein, as recorded in the field, is about 15 cm.

Methods of sampling and grade of ore

In order to obtain a fair idea about the grade of the various

types of ore bodies, several channel samples were collected from different parts of the mineralised zone. Channels of 2.5 to 5 cm wide and 2.5 cm deep across the chipped off faces of the exposed lodes were cut and the chips, fragments and dust were collected from each channel to make up a sample. However, owing to difficult accessibility of certain parts of the mineralised zone, it was not possible to maintain a uniform interval in the spacing of the channels. The lengths of the channels or the sampled widths of each sample are given in the table 7 . The locations of the channel samples have been marked on the plane table maps of the mineralized zone. The results of the neutron activation analyses of the samples are presented in table 7 .

In the upper mineralised zone the samples CS/8 and CS/9 were collected one meter apart from a small impersistent lode along a joint plane. Both the samples gave appreciable lead and zinc values, but the values of CS/8 (Pb 9.75% and Zn 5.46%) may not be true representative because the samples could not be taken along a channel owing to the brittle nature of the rock. In this case chip samples were collected from a block measuring 8 cm x 0.8 cm x 2.5 cm from the exposed face of the lode. The same was the case with CS/16 (Pb 8.03% and Zn 3.60%) taken from another lode. The maximum lead value (11.22%) was given by the sample CS/10 which was taken from a thin, short and isolated lode which is fairly rich in galena. Samples CS/11 to CS/16 were collected from the main lode and its offshoots, both localised along the joint planes. This lode is about 8 cm thick with sparse dissemination

TABLE - 7 Results of neutron activation analysis of samples from Rishi area

S.No.	Sample No.	Length of channel samples(cm)	Pb %	Zn %
1	CS/ 1	20	48.41	Trace
2	CS/ 2	22	2.29	0.14
3	CS/ 3	30	0.42	Trace
4	CS/ 4	97	0.40	Trace
5	CS/ 5	167	0.18	Trace
6	CS/ 6	23	7.19	Trace
7	CS/ 7	30	0.21	Trace
8	CS/ 8	8 x 8x 2.5	9.75	5.46
9	CS/ 9	28	4.48	0.42
10	CS/10	34	11.22	0.32
11	CS/11	29	2.23	2.00
12	CS/12	59	0.51	0.52
13	CS/13	72	0.43	0.80
14	CS/14	30	0.92	1.34
15	CS/15	38	0.95	0.20
16	CS/16	10 x 10 x 2.5	8.03	3.68

of sulphides on the footwall. The lead and zinc values in all these samples, except CS/16 varies from 0.42 to 2.23% and 0.20 to 2.00% respectively. In the lower mineralised zone the samples CS/4 and CS/5 were collected 1.2 inches apart and each almost covers the entire thickness of the mineralized zone. This zone contains a group of shear planes with lodes of galena and the intervening dolomite with the disseminations, stringers and clots of galena. Both sets of samples thus collected indicate low lead values and traces of zinc. However, the shorter channels across the individual shear planes gave assay values from 2.29 to 48.41% of lead. The sample CS/1, collected along a channel of 20 cm, is a part of galena vein, about 10 cm thick. The rest being crushed dolomites and quartz veins with rich disseminations of galena.

II. Copper deposits

The rocks in the area, older than Siwaliks, are traversed by numerous veins and stringers of quartz, but copper mineralization is mostly noticed in the chloritic and sericitic rocks. The country rocks in which the copper ores occur are slates, phyllites, schists and quartzites which form the Daling and Baxa Series of the Darjeeling Himalayas. In the Darjeeling district, a few occurrences have been reported from high grade metamorphic rocks of the transition zone between the Daling Series and the Darjeeling Series but not in the true Darjeeling gneissic rocks (Mallet, 1875). Bose (1891), however, reported several small and unworkable occurrences of copper from the

gneiss itself though usually closer to its junction with the Daling Series and identified pyrite, chalcopyrite with manganese minerals including bornite and pyrolusite in the ores, located at Lingni and Lindok in northeastern Sikkim, which are much beyond the present area. Recently the Geological Survey of India has also found a few occurrences of copper from the Darjeeling Gneiss Group but the report has not yet been published.

The phyllites, slates and schists of Daling series which are cupriferous, have frequent intercalations of quartzite and intrusions of quartz veins. It appears that the rocks have undergone folding subsequent to the intrusion of quartz veins with the result that the veins were not only deformed but also occur at many places as disconnected lenticles. Chalcopyrite and pyrite are associated with some of these stringers and lenticles of quartz veins. At places the slates have minute streaks of copper ores. Several massive ore bodies have also been noted at few places. There are also disseminations of chalcopyrite with pyrite in the quartzite bands of schistose rocks. Stains of malachite and limonite in the ore-rocks are quite common at a number of places.

Rare earths and thorium occur at several places independently and also in association with copper deposits elsewhere.

Copper occurrences of the following important localities have been studied in some detail.

A. <u>Peku area</u>

The copper deposits of Peku occur in a terrain, which is deeply

dissected by the Rimpi Chu (river) and its tributaries. The mineralised area is about 3.2 km WNW of Temi in West Sikkim. The country-rocks are essentially chlorite-phyllites with some interbands of quartzite. The strike of both the bedding and the foliation of the country rocks are the same and varies from E-W to NW-SE with moderate northeasterly dip. The country rocks have a number of shear planes striking mostly along the foliation direction (Fig. 3). There are a few thin sills of basic rocks within the phyllites. A dark grey variety of asbestos is developed in these basic rocks particularly near their contact with quartz veins.

The primary sulphide minerals like chalcopyrite, pyrrhotite and pyrite occur in association with quartz veins, disposed along the schistosity, shear planes and fracture cleavage of the phyllites. In cases, where the mineralized quartz veins are guided by the shear planes, the ores show little or no dispersion across the shear planes. It has already been stated earlier that the quartz veins contain two types of quartz, viz., i) grey and cherty, and ii) white and semi-vitreous. The sulphide minerals are associated with the first type. The mineralised veins are largely confined to a zone whose length is 370 m and breadth 4 m. The quartz veins within this zone, as exposed along a new road cutting, range from 3 m to 50 m in length and 10 cm to 1 m in thickness. The veins are mostly lensoid in shape and generally the ore is lean. The richest lenses of quartz vein exhibit crushed margins and concentration of chalcopyrite near the core region.

Method of sampling and grade of the ore

The channel samples were collected along the channels 2.5 cms wide and 1.2 cms deep by chiselling along the thickness of the individual mineralized veins. Some parts of the footwall and the hanging wall with poorly dispersed sulphides were also sampled.

The results of the neutron activation analysis of the samples are presented in table 8.

The channel samples T/12 and T/13 (Cu - 7.93%) fall on the lode which represents the richest part of the mineralised zone. One continuous channel across the lode was subdivided into two parts viz., T/12 (Cu - 1.15%) representing the bottom 30 cms of the thickness of the lode and T/13, the top 25 cms. The average assay of the lode at this portion of the mineralised zone is, therefore, 4.80% of copper. Other channel samples in this area have 1.28% of copper.

The mineralized area has been mapped on a scale 1:1000. The map (Fig. 3), thus produced, depicts the distribution of the mineralised veins in the rocks and locations of channel samples for chemical analysis.

The mineralised zones in this area has a strike length of about 370 m. The exposures of the lodes are, of course, interrupted by deeply cut valleys, covered with debris and steep soil covered ridges with abundant vegetation.

This copper deposit was found to be associated with rare earths and thorium through radiometric surveys.

TABLE - 8 Results of neutron activation analysis of samples from Peku area

S.No.	Sample No.	Length of channel sample (cm)	Cu %
1	T/1	20	0.48
2	T/2	92	0.36
3	T/3	60	0.48
4	T/4	22	0.02
5	T/5	20	Trace
6	T/6	117	Trace
7	T/7	50	1.26
8	T/8	42	Trace
9	T/9	30	Trace
10	T/10	30	0.13
11	T/11	35	0.06
12	T/12	30	1.15
13	T/13	35	7.93

B. Legship area

About 300 m from the Kalej bridge on the Legship-Nayabazar road on the right bank of the Ranjit river, sulphide ores occur in the quartzites and chlorite-sericite phyllites belonging to the Daling Series. Disseminated chalcopyrite-pyrite ore was found in a band about 0.5 m thick, exposed along a road cutting. The mineralization is associated with sheared quartz veins intruding into the quartzites and phyllites. The sulphide ores are, however, more concentrated in the phyllites and quartzites than in the quartz veins in this area.

Disseminations of pyrite are found in sheared quartz veins and the associated quartzites and phyllites over a length of about 40 m, exposed in a road section (Fig. 2). Innumerable quartz veins, either barren or limonite-bearing occur all over the area. Siderite is associated with these quartz veins at the confluence of the Ranjit river and the Kalej Chu.

Along the scarp face high up on the right bank of Ranjit river, evidence of mineralisation is rather meagre. However, to detect the concentration of Cu, Pb and Zn in traces, plant and rock samples were collected along a particular direction on this ridge and also along another direction on the left bank, in order to detect the extension of mineralisation, if any. The samples were collected at an interval of 10 m, as far as possible. On the right bank, samples could not be collected along a straight direction on account of difficult accessibility on the ridge face. The results of

chemical analysis are presented in Table 9.

C. Sikhip mines

In the Sikhip mines the ore is confined to the Baxa phyllites and slates interbanded with quartzites. The mineralised zone is located near the suspension bridge, on the eastern side of Ranjit river (Fig. 8) about 8 kms from Nayabazar on the Gezing road. The terrain is deeply dissected by Ranjit river and exhibits a typical hilly topography of Lesser Himalayan Ranges.

The rocks in the area consist partly of Lower Gondwana formations (Sandstones, conglomerates and shales, etc.) exposed as a tectonic window and partly of dolomitic limestones, phyllite, slates and quartzites of Baxa Series. In the mineralized area the country rocks are highly altered. They are typically silicified and chloritic, sericitic, dolomitic and cherty in nature. The Baxas and Gondwanas have also some sills of lamprophyres which were also altered. The country rocks are highly folded and the associated quartz veins, which intruded along the foliation planes of the rocks, are drawn out into lenses. The general strike direction of the rocks belonging to Baxa Series is more or less the same as that of the Gondwanas and it changes from E-W to WNW-ESE. Dip is northeasterly at angles varying from 15° to 45° (Fig. 8).

The ores, like all the other copper occurrences of this part of Eastern Himalayas, are confined to a hard jaspery, chloritic, sericitic, dolomitic and silicified rocks. The chalcopyrite-pyrite bearing quartz veins occur along the schistosity, shear planes and

TABLE - 9 Results of chemical analysis of plant samples collected from the Lagship area

No.	Cu (ppm)	Pb (ppm)	Zn (ppm)
1	100	< 50	200
2	50	< 50	200
3	125	< 50	100
4	75	< 50	100
5	100	< 50	200
6	50	< 50	200
7	50	< 50	200
8	< 50	< 50	100
9	11	< 50	50
10	200	< 50	100
11	200	< 50	75
12	50	< 50	100
13	100	< 50	50
14	150	< 50	100
15	50	< 50	50
16	75	< 50	250
17	50	< 50	50
18	75	< 50	150
19	< 50	< 50	< 50
20	100	< 50	< 50
21	75	< 50	< 50
22	100	< 50	< 50
23	50	< 50	100
24	125	< 50	150
25	250	< 50	150
26	75	< 50	100
27	75	< 50	100
28	50	< 50	< 50
29	200	< 50	300
30	100	< 50	100
31	50	< 50	50
32	500	< 50	100
33	100	< 50	150
34	75	< 50	100
35	400	< 50	200
36	300	< 50	100
37	< 50	< 50	< 50
38	150	< 50	250
39	1000	< 50	400
40	300	< 50	100
41	150	< 50	< 50
42	100	< 50	50
43	50	< 50	< 50
44	300	< 50	200
45	50	< 50	100

fracture cleavage of these rocks. The sulphide ores show very little dispersion where the mineralisation was controlled by the shear planes. Elsewhere they have no such control. Like all other sulphides occurrences of Sikkim and Darjeeling District, the quartz veins in this mineralised zone also are typically of two varieties viz., i) grey, cherty type, and ii) white, semi-vitreous quartz belonging to a different generation. The sulphide minerals are typically associated with the first variety. The mineralized veins are found to be restricted to a zone of 15 m long and 1 m wide. The individual mineralised veins are 5 to 16 cm thick. There are three ore zones at vertical intervals of 10 to 12 ft. The copper lodes were workable at one time in the past as indicated by three abondoned mines, located on the face of a prominent fault scarp, which more or less follows the axial plane of a plunging anticline in a NW-SE direction for about a km. The deposit was located along this fault zone and within a distance of 3/4 km from the Baxa-Gondwana boundary. Shear joints are common in the mineralised zones. The Gondwana rocks in the area have also some minor inclusions of sulphide ores. The neutron activation analysis of a few such samples of Gondwana rocks have shown the presence of copper. The geochemical surveys have also given the same evidence.

A geological map of the area around the Sikhip copper mines has been constructed with the help of plane table on a scale of 20 cm = 1 km. The geochemical and radiometric investigations around Sikhip have revealed significant anomalies of some radioactive

elements in the copper deposits and elsewhere in the area. The radioactive elements are some rare earths and thorium. They are partly associated with zones of copper mineralisation and partly form independent zones. The radioactive zones have been plotted on the geological map (Fig. 3). The rare earths, being highly radioactive, could be easily detected by radiometric and by chemical analysis of the samples collected from the area. In some cases they served as mineral guides to locate several unknown copper bearing veins and the disseminated ore bodies not only in this area but throughout the region.

Methods of sampling and grade of the ore

Sampling of the mineralized zones was carried out and channel samples were collected from different parts of the mineralized zones in order to have an idea of the grade of the ore bodies. Channels of dimensions 2.5 to 5 cm wide, 2.5 cm deep and of various lengths were out. The samples including the chips, fragments and dust, drawn from each channel, were collected. As the mineralized zones are located on a steep wall-like fault scarp, it was not possible to maintain equal spacing for the channel samples drawn. The results of the neutron activation analysis of samples are presented in table 10.

Manganese was found to be associated with copper and the percentage of Mn varies with respect to the increase in the percentage of copper. A maximum of more than 1 % Mn was found in channel sample number CS/6. Samples drawn from channel samples, CS/1, CS/5,

TABLE - 10 Results of neutron activation analysis of samples from Sikhip area

S.No.	Channel sample No.	Length of channel samples (cm)	Cu %	Mn %
1	CS/ 1	20	7.78	0.3
2	CS/ 2	24	1.34	< 0.004
3	CS/ 3	35	0.96	0.02
4	CS/ 4	40	< 0.03	0.001
5	CS/ 5	100	4.5	0.05
6	CS/ 6	200	5.6	1.01
7	CS/ 7	25	3.8	0.43
8	CS/ 8	22	1.1	0.001
9	CS/ 9	32	0.33	0.028
10	CS/10	68	1.08	0.024
11	CS/11	38	1.02	0.31
12	CS/12	35	0.11	0.01
13	CS/13	60	0.85	0.04
14	CS/14	110	2.21	0.51
15	CS/15	115	0.01	0.003
16	CS/16	135	0.09	0.002
17	CS/17	139	0.04	0.001
18	CS/18	178	0.11	0.09
19	CS/19	20	0.5	0.08
20	CS/20	62	0.03	0.002

CS/6, CS/7 were taken from the rich ore zones and therefore, the percentage of copper in them is high. However, an average of maximum of 1% Cu may be taken for this copper deposit.

D. Rohtak khani or Manpur mines

The zone of sulphide mineralisation is situated three miles due south of Namchi, along a feeder road to Manpurkhola (Fig. 2). It is one of the most promising area in western Sikkim. Three adits are excavated by the ancient miners and then abandoned. The mineralisation is confined to the quartz veins in silicified and chloritic phyllites, slates and quartzites belonging to Daling Series. The primary ore minerals are mainly chalcopyrite and pyrite. Malachite and azurite are confined to the borders of quartz veins.

A similar type of minor mineralisation was also located along a road section north of this mineralised zone, about 3 miles away from Namchi on the Temi road, near Nik village. But this deposit occurs mostly in a disseminated state.

Both the occurrences of copper are located very near to the Daling-Gondwana thrusted boundary. Thorium and rare earths were also detected in these copper deposits as well as in other adjacent zones devoid of copper.

E. Roathak or Jagdum mine

It is an abandoned old working of copper, which is situated at Rothakhani, NNE of the village Chakung in west Sikkim (Fig.2). The ores are

associated with the quartz veins intruded along the foliations of Daling phyllites and slates. The mineralisation is confined to the eastern side of a deep and inaccessible ravine along a fault zone. The ore is mainly chalcopyrite with some pyrite. Here also the mineralised zone is very close to the thrusted boundary of the Dalings and Gondwanas.

F. Kalimpong mines

Some old abandoned mines are located 2 miles NE of Kalimpong, Darjeeling district, West Bengal. The area around the mineralized zones is faulted and tectonically disturbed (Fig. 1). The mineralization is also controlled by the shear joints running in an E-W direction. This set of joints is typically mineralised by base metal deposits, and the rare earth elements and thorium. Mineralisation is mainly confined to the quartzites with some disseminations in the phyllites and slates. The country-rocks are highly disturbed and contorted. There are two closely spaced adits, the larger one extends for about 50 ft along the strike of the rocks and has a maximum height of 10 or 12 ft. The quartz veins, in which pyrite and chalcopyrite occur, are irregular or lenticular in shape. The mineralisation is structurally controlled and is confined to the shear zone. High radioactivity due to the presence of thorium and rare earths was also detected in these deposits and also in the adjacent localities where no sulphide ores occur (Fig. 1).

The results of the neutron activation analysis of the channel samples collected from the mineralised zone are given in Table.11 .

TABLE - 11 Results of neutron activation analysis of the samples from Kalimpong

S.No.	Channel Sample No.	Cu%	Mn%
1	KCS/1	0.14	0.06
2	KCS/2	0.21	0.01
3	KCS/3	0.03	0.003
4	KCS/4	1.21	0.51
5	KCS/5	3.41	1.11
6	KCS/6	1.10	0.09
7	KCS/7	0.80	0.06
8	KCS/8	0.20	0.05
9	KCS/9	0.01	0.04
10	KCS/10	0.50	0.01

A maximum value of 3.41 % Cu was given by the channel sample number KCS/5. The sample numbers 4, 5 and 6 gave higher values of copper content because they were drawn from the rich zones. However, the deposits has on the average a value of 0.5 % Cu.

G. Pachikhani mines

The old and abandoned copper mines at Pachikhani by the side of Pakhyong-Gangtok Road about 1 mile from the Rorethang road bridge. The area around the Pachikhani mines is mainly composed of Daling phyllites, slates and quartzites. The Darjeeling gneisses also occur mainly in the northeastern, southwestern and southeastern sides of the area (Fig. 5). The general strike of the country rocks around the mineralised zones varies from WNW-ESE to NW-SE. The ore

are mainly composed of chalcopyrite, pyrrhotite and pyrite. The mineralisation is close to the junction of two major faults and controlled by three fractured zones running in an ENE-WSW direction. The ores are mainly associated with quartz veins emplaced along the planes of foliation and east-west trending sheared joints of the country rocks. There are three small mineralized zones separated by a distance of 8 to 10 ft from one another. The sulphide mineralization in this area is also associated with rare earths and thorium bearing group of minerals which form separate zones close to the copper lodes.

Channel samples were collected from the mineralised zones in order to assess their copper contents. Channels were cut from 3 to 5 cms wide and 2 to 3 cms deep. Their lengths are variable. The results of the neutron activation analysis of the samples are presented in the Table 10.

Copper recorded higher values in the samples Nos.CS/P-8,9,10,12, 13,18 and 20, all of which have been drawn from rither parts of the ore zones of copper. The average copper content in this deposit is about 1%. Copper is associated with corresponding high values of manganese with a maximum of about 1%. This deposit has been worked out earlier also, and has still the potentialities. A number of other small occurrences of copper in continuation with this deposit have been noted. A very rich copper

TABLE - 12 : Results of neutron activation analysis of samples from Pachikhani mines

S.No.	No. of channel sample	Length of channel (cm)	Cu %	Mn %
1	CS/P- 1	20	0.02	0.008
2	CS/P- 2	40	0.01	0.009
3	CS/P- 3	30	0.05	0.008
4	CS/P- 4	15	0.07	0.006
5	CS/P- 5	15	0.01	0.004
6	CS/P- 6	25	0.14	0.08
7	CS/P- 7	30	0.15	0.08
8	CS/P- 8	80	1.12	0.06
9	CS/P- 9	110	4.32	1.02
10	CS/P-10	100	1.12	0.18
11	CS/P-11	75	0.5	0.09
12	CS/P-12	150	5.16	1.41
13	CS/P-13	79	1.12	0.28
14	CS/P-14	68	0.61	0.03
15	CS/P-15	45	0.02	0.004
16	CS/P-16	30	0.01	0.003
17	CS/P-17	15	0.05	0.008
18	CS/P-18	95	1.11	0.09
19	CS/P-19	110	0.12	0.08
20	CS/P-20	90	2.14	0.21

bearing zone has been located by the author near the junction of the two faults close to the Rorethang bridge. This zone was exposed during the blasting operation for the construction of a road bridge in 1970.

H. Rangpo mines

The copper mines at Rangpo are located about 1 mile north of the junction between Tista and Rangpo rivers which is close to Rangpo town and about 10 miles WSW of Pachikhani mines.

Here the country-rocks are chlorite-, sericite-, biotite-schists, and phyllites and quartzites belonging to Daling Series. There are also some outcrops of granodiorite gneiss belonging to the Darjeeling Series (Fig. 18).

The important ore minerals are pyrrhotite, chalcopyrite, sphalerite and galena in order of relative abundance. The other ore minerals are pyrite, chalcocite, etc. The mineralisation is structurally controlled and the ore bearing quartz veins have followed the fractured zones and shear planes. Shear joints with mineralised veins trend in an almost E-W to ENE-WSW directions.

The mineralisation is confined to the southern limb of a major plunging anticlinal structure. There are two distinct mineralised horizons and both of them occur in the schistose and phyllitic rocks separated by about 40 feet of barren quartzites. The country-rocks generally strike in NE-SW directions. Rangpo copper lode is exposed adjacent to a normal strike fault on the surface. The mineralized wall-rocks are highly altered with prominent zones showing chloritization,

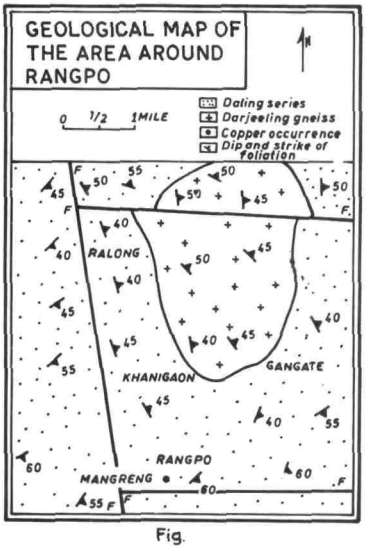

GEOLOGICAL MAP OF THE AREA AROUND RANGPO
0 1/2 1MILE
Daling series
Darjeeling gneiss
Copper occurrence
Dip and strike of foliation
RALONG
KHANIGAON
GANGATE
RANGPO
MANGRENG

Fig.

Fig. 18

biotitization and sericitization. Here the rocks are more coarse-grained than the adjacent unaltered rocks. The ores occur in veins, pockets, etc. Disseminated grains and clots of ore in the host rocks are also common.

The samples were drawn from the channels measuring 2.5 cm to 5 cm wide, 3 to 5 cm deep. Length of the channels are variable. The results of neutron activation analysis of the samples are presented as follows:-

TABLE - 13 Results of neutron activation analysis of samples from the Rangpo area.

S.No.	Channel sample No.	Length of channel (cm)	Cu %	Zn %	Pb %	Mn %
1	CS/R- 1	20	0.54	0.06	0.08	0.04
2	CS/R- 2	80	0.06	0.002	0.007	0.003
3	CS/R- 3	110	1.01	0.11	0.75	0.21
4	CS/R- 4	150	0.51	0.06	0.08	0.06
5	CS/R- 5	40	1.88	0.19	0.41	0.3
6	CS/R- 6	15	0.02	0.004	0.006	0.001
7	CS/R- 7	80	0.31	0.04	0.06	0.002
8	CS/R- 8	35	0.11	0.06	0.09	0.008
9	CS/R- 9	15	0.02	-	-	0.002
10	CS/R-10	20	0.04	-	-	0.004

The analyses show only that the sample Nos. CS/R-3 and 5 have sufficiently higher content of copper. The average grade of copper was found to be about 0.1 to 0.2%. The copper ore is also associated with some traces of Pb, Zn and Mn.

I. Other occurrences

Several other hitherto unknown minor occurrences of pyrite

and/or chalcopyrite in the form of disseminations in quartz veins in the Daling Series were recorded from a number of localities like Thurang Khola, Lish Khola, Lethi naddi, Rambi nala, Chel river, Sukna Khola, Mangzing Khola, Rilli naddi, Suruk Khola, Samthong Khola, Rayeng Khola, Kali Khola, Siti Khola, Dam Khola, Mana Khola, Mahan nadi, etc., along the eastern and western banks of Tista river, in Darjeeling district (Fig. 1).

Chapter VI

MINERALOGY OF THE ORE DEPOSITS

An attempt has been made to identify the important metallic minerals which are associated with the sulphide ore deposits of the study area with the help of ore-microscope. A few other minerals were identified by their characteristic powder pattern in X'-rays (Table 14). The texture of some of the ores and their mineral paragenesis have also been taken into consideration but with certain limitations. The main purpose of this work is, however, to present the mineralogical characters of the ore-forming minerals and their assemblages on the basis of their optical properties, etch reactions, etc.

Such hypogene ore minerals as chalcopyrite, chalcocite, pyrrhotite, pyrite, arsenopyrite, galena, sphalerite and bismuthinite have been identified. The supergene minerals in these deposits include covellite, chalcocite, enargite, malachite, azurite, limonite, anglesite, cerussite, dundasite, rozenite, pyromorphite and mimetite.

A. Hypogene minerals

The mineralogical and other characters of the different hypogene ore minerals, identified in the polished sections under the reflected light, have been presented as follows:

1. Pyrite and marcasite (FeS_2)

Pyrite is the most abundant mineral in the copper as well as in the lead-zinc deposits. Since minor amount of marcasite occurs always in association with pyrite, the former is, therefore, discussed with pyrite.

Cubes, pyritohedrons, or irregular masses of pyrite, sometimes with marcasite, occur in the lead-zinc ores and their host rocks dolomitic limestones and also in the copper deposits and their host rocks as slates, phyllites, quartzites and schists.

The pyrites, which are associated with the copper deposits, are sometimes fractured and crushed and largely restricted to the ore zones, whereas those which are related to the lead-zinc deposits, are unfractured and occur in a disseminated state in the lodes as well as in the wall-rocks. In fact pyrite is a ubiquitous mineral in the sulphide lodes of the area. Marcasite is associated with pyrite but its crystal size is submicroscopic in some ores.

Pyrites are generally idiomorphic, coarse- to fine-grained, the average diameter of the grains is 0.24 m, while the pyrite crystals are either euhedral or subhedral (Plate XX, Fig.1), the grains of marcasite are mainly anhedral in shape.

In a few polished sections of copper ores, pyrite has been partly or wholly replaced by chalcocite. There are some irregular inclusions of gangue minerals in pyrite.

Colour	Creamy to yellowish white
Polishing behaviour	Moderate
Cleavage	Cubic
Reflectivity	Higher than the surrounding minerals (chalcopyrite and chalcocite, etc)
Crossed nicols	Isotropic

Etch reactions

HNO_3 (1:1)	Sometimes stained greyish brown: fumes tarnish it readily.
HCl (1:1)	Negative
$FeCl_3$ (1:1)	
$HgCl_2$ (sat.)	
KOH (sat.)	
KCN (20 %)	

2. Arsenopyrite (Fe As S)

Arsenopyrite is found only in the copper deposits at Rangpo, Peku and Pachikhani. The mineral grains are generally fine and occasionally coarse with two sets of well-developed cleavages. The grains are anhedral and their margins are generally found to be irregular.

Colour	White with creamy tint
Polishing behaviour	Moderate
Reflectivity	Slightly lower than pyrite

Etch reactions

HNO_3 (1:1)	Positive - Tarnished to deep brown
$HgCl_2$ (sat.)	Positive - Tarnished yellowish brown
KCN (20 %)	Positive - Tarnished pale yellow
HCl (1:1)	Negative
$FeCl_3$ (1:1)	
KOH (sat.)	

3. Pyrrhotite (FeS)

Pyrrhotite, which also occurs commonly in the Rangpo, Peku and Pachikhani copper ore deposits, is not found in any other copper deposits of the area. Inclusions of quartz and carbonate gangues within pyrrhotite are common. The mineral grains are generally coarse to medium grained, and frequently fractured to a great extent (Plate XX, Fig. 2). It is commonly associated with pyrite.

Colour	Pale creamy brown.
Reflectivity	Lower than pyrite, chalcopyrite and other surrounding minerals.
Polishing behaviour	Good
Anisotropism	Strong (light grey, bluish grey to brown).

Etch reactions

HNO_3	(1:1)	Positive - slowly stained brown, fumes tarnish permanently. Few grains give negative results.
HCl	(1:1)	Almost negative - fumes tarnish feebly.
KOH	(sat.)	Positive - Slowly turned brown to irridescent.
$FeCl_3$	(1:1)	Negative
$HgCl_2$	(sat.)	
KCN	(20 %)	

4. Chalcopyrite ($Cu\ Fe\ S_2$)

Chalcopyrite is readily distinguished by its brass yellow colour. It occurs in granular aggregates and clots, and the individual grains being more or less equidimensional, irregularly rounded or anhedral. The average diameter of the grains is 0.112 mm and their maximum size of diameter never exceeds 3 mm. It also occurs in the form of thin irregular veins or stringers in vein quartz (Plate XX, Fig. 3).

Mainly quartz, occasionally talc and dolomite occur as gangue inclusions.

Colour	Bright and brass-yellow with shades of green.
Reflectivity	Lower than pyrite.
Anisotropism	Poor - with greenish yellow to greyish-blue colours.

Etch reactions

HNO_3	(1:1)	Positive reactions, fumes tarnish the surface.
HCl	(1:1)	Negative
$FeCl_3$	(1:1)	
$HgCl_2$	(sat.)	
KOH	(sat.)	
KCN	(20 %)	
Aqua Regia		Slowly tarnished to a persistent brown colour, fumes tarnished differently and sometimes grain-boundaries were developed.

The surface area of the ore sample was etched by a saturated chromic acid solution for more than 45 minutes, and well-developed twin-lamellae of peculiar style were noted. No doubt, such features sometimes result due to the imperfect or differential polishing of the sample. The twin lamellae observed, are found to be lanceolate in shape. According to Vance (1961) such tappering spindle-shaped twin lamellar features in the silicates, especially, feldspars always resulted due to the action of tectonic forces. Their crystallographic directions are also not uniform and are thus aligned to more than one direction. Richard (1955) and Ramdhor (1960) have interpreted such twin-lamellar features as related to tectonic forces. Richard (1955) has observed identical lanceolate and spindle-shaped twins in the crushed, and brecciated ore samples of chalcopyrite. Ramdhor (1960)

described them as metamorphic twin lamellae. Spindle-shaped twin lamellae observed in a few chalcopyrite samples of the area thus reflect the possibility of a period of deformation after the crystallization of chalcopyrite.

5. Galena (PbS)

Galena is the principal hypogene sulphide ore mineral in the lead-zinc lodes with sporadic crystals of sphalerite and pyrite. No doubt galena figures largely in the Pb-Zn deposits of the area but it is also sometimes found as a minor constituent in copper ores. In the Pb-Zn deposits of Rishi area, it is located in the fractured and sheared horizons of the dolomitic limestones and dolomites of Baxa Series. Galena occurs in the fracture spaces, vugs and cavities of the country-rocks. Sometimes the cleavage partings of the dolomite are mineralized with galena. Disseminations and tabular bodies of galena also occur frequently in the silicified dolomitic limestones. In places beautiful crystal groups, individual cubo-octahedral crystals, and twins are present, particularly in the drusy parts of the lodes. Where brecciation has occurred and slips and minor faults slice through the lodes, galena was subjected to intense shearing and deformation due to which it appears highly folded (Plate XX, Fig. 4).

The gangue is mainly composed of quartz, jasperoid, dolomite and calcite. Presence of thin veins of galena along the cleavage and the intragranular spaces of the gangue minerals are very common. The gangue minerals, particularly calcite, offers automorphic outline with the replacing galena along the cleavages.

Colour	White
Reflectivity	High
Cleavage	Well developed, prominent triangular pits are found at the points of intersection of cleavages.
Crossed nicols	Isotropic; occasionally shows a weak anomalous anisotropism.

Etch reactions

HNO_3	(1:1)	Quickly stained blue black commonly without any effervescence.
HCl	(1:1)	Tarnishes brown to iridescent.
$FeCl_3$	(1:1)	Stains iridescent.
$HgCl_2$	(sat.)	Negative.
KOH	(sat.)	
KCN	(20%)	

Galena was found to be oxidised to anglesite and cerrusite. These minerals are developed particularly along the cleavage planes of galena in the form of small tongues and seams. In comparison to the splendent and metallic lustre of fresh galena, the oxidised portion has a dull lustre.

6. Sphalerite (ZnS)

Sphalerite occurs in only two localities and is usually associated with lead-zinc ores. A few copper ores also have minor amounts of sphalerite. It is not as abundant ore mineral as galena and occasionally occurs as minute veins and stringers. In the brecciated parts of the lodes sphalerite is sheared and highly crushed and in places, it is recemented by quartz, calcite and siderite. In the oxidised parts it is present in limonitic boxwork.

It is medium-to coarse-grained and occasionally, shows euhderal outlines. When associated with galena, it exhibits a mutual boundary relation with the latter. The sphalerite grains have generally irregular contact with galena and gangue. Sphelerite in copper ores was found to replace chalcppyrite to a limited extent (PlateXXI, Fig. 1). Generally in most oxidised ores sphalerite has been almost completely removed leaving only limonitic and siliceous boxworks.

Colour	Grey to dark grey
Internal reflection	Distinct
Twinning	Broad lamellar twin
Reflectivity	Low
Crossed nicols	Isotropic

Etch reactions

HNO_3	(1:1)	Positive - fumes tarnish
HCl	(1:1)	Positive - fumes tarnish
KCN	(20 %)	Negative
$FeCl_3$	(1:1)	
KOH	(sat.)	
$HgCl_2$		

7. Bismithunite (Bi_2S_3)

Small grains of bismithunite are found at the sphalerite gangue, and galena-gangue contacts.

Colour	Galena white
Anisotropism	Strong (varying from olive to greyish pink).
Cleavage	One set

B. Supergene minerals

The principal supergene minerals, which have been identified include limonite, cerussite, anglesite, malachite, azurite, covellite and chalcocite.

1. Limonite ($H\ FeO_2\ nH_2O$)

The term limonite, as used here, includes varieties of the hydrated iron-oxides. Limonite is also found to be intimately mixed with small amounts of other supergene minerals.

The nature of occurrence varies from ochreous and earthy material coating ore and gangue minerals and rock fragments, to clinker-like, botryoidal and hard compact masses cementing the vein breccia and nodules of ores. There are also some pseudomorphs of limonite after pyrite.

Colour	Grey-white to grey
Reflectivity	Very low; earthy appearance
Pleochroism	Slight
Anisotropism	Distinct

2. Cerussite ($Pb\ CO_3$)

Cerussite is widely diffused in the oxidised parts of the lodes, where it is generally intimately associated with limonite, anglesite, and other supergene minerals. Its identification was confirmed by X'-ray analysis. It is generally white to grey in colour. Sometimes it is present as earthy coatings, pulverulent disseminations and ramifying networks of small micro-crystalline masses in the oxidized lead ores. Sometimes clusters and irregular aggregates of small tabular and

elongated crystals of cerussite occur in the oxidized parts of galena and in limonitic boxworks.

Cerussite is characteristically associated with anglesite in some specimens.

3. Anglesite ($PbSO_4$)

Anglesite is an important secondary lead mineral and it is generally associated with galena and sometimes with limonite, cerussite, malachite and azurite. The identification of anglesite was confirmed by the X'-ray analysis of its powder. Anglesite is light to dark grey in colour and generally occurs as earthy coatings around nodules and crystals and grains of galena. Both cerussite and anglesite are found to be present along the fractures and cavities in the limonite boxwork within the oxidized lead ores.

4. Pyromorphite and mimetite $Pb_5(PO_4, ASO_4)_3 Cl$

The two minerals which are rare and closely associated were identified by X'-ray analysis. They are restricted to the vugs and cavities of the ore in association with other minerals like anglesite, cerussite, and limonite. Pyromorphite and mimetite are greyish green to yellowish brown in colour and occur as globular to acicular crystals.

5. Dundasite, $PbAl_2(CO_3)_2(OH)_4 2H_2O$

Dundasite is a rare hydrated basic carbonate. It was identified by X'-ray examination of white to faintly yellowish material found to occur as encrustations in the vuggy parts of the oxidised ore. The

mineral is characteristically associated with cerussite.

6. Rozenite ($FeSO_4\ 4H_2O$)

Rozenite is a rare tetrahydrate of ferrous sulphate, which has been introduced to literature by Kubisz (1960) who named and described it as 'Rozenite'. The mineral was identified by X'-ray examination in five oxidised ores. It occurs as microcrystalline coatings on the surface of pyrite, and as colourless to white earthy encrustations on the surface of the oxidised ores.

7. Chalcocite (Cu_2S)

It is a common ore mineral in the copper deposits, and its grain boundary is irregular. It is clearly associated with chalcopyrite. Chalcocite also occurs in the form of reticulated veins and irregular patches, and replaces chalcopyrite and pyrite (Plate XXI, Figs. 2). It often shows typical colloform bands.

Colour	White to grey with bluish tint
Form	Massive as well as colloform
Reflectivity	Lower than chalcopyrite. It is typically isotropic and occasionally shows anisotropism.

Etch reactions

HNO_3	(1:1)	Positive	Strong effervescence, stained bluish black
HCl	(1:1)	Negative	
$FeCl_3$	(1:1)	Positive	Stained bluish, grey, no etch cleavage.
$HgCl_2$	(sat.)	Negative	
KCN	(20%)	Positive	Quickly turned black leaving a rough surface.
KOH	(sat.)	Negative	

8. Covellite (CuS)

Covellite is a minor constituent of the copper ores. There are some skeletal crystals of covellite which replaced chalcopyrite.

Colour	Deep blue with violet shades.
Reflectivity	Slightly more than to almost equal to chalcocite and lower than chalcopyrite.
Crossed nicols	Anisotropism strong.

Etch reactions

KCN	(20%)	Positive	Stains black
HNO_3	(sat.)	Positive	Fumes tarnish
$HgCl_2$	(sat.)	Negative	
KOH	(sat)	Negative	
$FeCl_3$	(1:1)	Negative	
HCl	(1:1)	Negative	

9. Enargite (Cu_3AsS_4)

Enargite is associated with chalcopyrite, pyrite and pyrrhotite in some of the copper ores. The grain boundaries are irregular and it often replaces pyrite and pyrrhotite (Plate XXI , Fig.3). Often its cleavges are distinct.

Colour	Grey to greyish-white, sometimes pinkish.
Crossed nicols	Strong anistropism with greyish and reddish shades.

Etch reactions

KCN	Stains dark
HNO_3	Faintly tarnishes
$FeCl_3$, KOH, HCl	Negative

10. Malachite $Cu_2(OH)_2(CO_3)$ and Azurite $Cu_3(OH)_2(CO_3)_2$

Malachite and azurite generally occur together and are commonly found in association with chalcopyrite. Masses and radiating clusters of micro-crystals are common in places.

a) Malachite

Chalcocite and covellite have been veined and replaced by malachite. But malachite is also veined and replaced by azurite and limonite.

Colour	Grey with greenish tint.
Reflectivity	Higher than gangue but in general low.
Internal reflection	Well-marked with light to dark grey green colours.

b) Azurite

Azurite is very much restricted to open spaces, vugs and cavities in the highly oxidised ores.

Colour	Deep greyish blue with typical earthy appearance.
Reflectivity	Slightly higher than the gangue but otherwise in general low.
Crossed nicols	Bright blue colours.

Note: See table 14 on the next page for X'-ray analysis data of some supergene minerals described earlier.

TABLE - 14 X'-ray analysis of some of the supergene minerals

S.No.	Minerals		$d\mathring{A}$	I/I_1
1	Anglesite	$PbSO_4$	3.88	85
2	Pyromorphite	$Pb_5(PO_4\ AsO_4)_3\ Cl$	2.04	80
3	Mimetite	$Pb_5\ [(As,P)O_4]_3\ Cl$	2.98	100
4	Cerussite	$PbCO_3$	3.51	42
5	Dundasite	$PbAl_4(CO_3)_4(OH)_8\ 3H_2O$	3.61	81
6	Rozenite	$FeSO_4 \cdot 4H_2O$	3.99	82

Assemblage of ore-minerals and their textural relations

The mineralogical study of the copper and lead-zinc ores has revealed interesting textural relationships among certain ore minerals which are grouped into sets of assemblages and discussed as follows:

Associated with copper occurrences:

1) Pyrite-Arsenopyrite-pyrrhotite-chalcopyrite

Arsenopyrite has been partly replaced by pyrrhotite (Plate XXI, Fig. 4) chalcopyrite and other sulphides both along fractures and margins. Pyrite is represented by cubic and sometimes rounded grains. Occasionally, chalcopyrite occupies the intergranular spaces of pyrite. The pyrite-chalcopyrite relationship is sometimes obliterated due to the intervention gangue minerals, and sometimes by the development of chalcocite at the contact of the two minerals. In some pyrites there are microveins of chalcopyrite. There has been, however, no evidence of replacement of pyrite by chalcopyrite anywhere, including along their contacts.

Pyrrhotite has been slightly replaced by pyrite. Tongues and protrusions of pyrite are also found in pyrrhotite. But frequently, the two minerals show mutual boundary relation with one another (Plate XX, Fig. 1). It indicates that probably the crystallisation of pyrrhotite started first and the deposition of pyrite followed immediately. However, age relation between the two minerals may be generally overlapping.

The above textural features, therefore, indicate that the

mineralization of arsenopyrite was followed successively by pyrrhotite, pyrite and chalcopyrite.

2) Pyrrhotite-chalcopyrite-sphalerite-galena

Sphalerite and galena are the minor mineral constituents in these ores. Sphalerite is intimately associated with pyrrhotite and chalcopyrite, and occurs generally along the pyrrhotite-gangue, or chalcopyrite-gangue boundaries. Pyrrhotite and chalcopyrite are also partly replaced by sphalerite (Plate XXI, Fig. 1). There are veinlets of galena in sphalerite. The crystals of galena always have bold advancing contacts with those of sphalerite, indicating that galena is younger to sphalerite in age.

3) Pyrite-chalcopyrite-covellite-chalcocite

Chalcocite replaces chalcopyrite and pyrite, showing a 'mesh structure'. Textures of 'relict type' are sometimes found, where minute remnants of pyrite may be found in chalcocite areas. Two generations of chalcocite have been recognised. The variety which replaces pyrite is the greyish white with bluish tint while the other one replacing chalcopyrite is bluish white in colour. Sometimes the presence of covellite around chalcopyrite shows 'rim replacement texture'. Often chalcopyrite has innumerable fracture veinlets of chalcocite with matching boundary walls. Covellite appears to be older than chalcocite in age.

Enargite is a minor mineral constituent in these ores. It has partly replaced pyrite along grain boundaries and sometimes found

enveloping pyrite (Plate XXI, Fig. 3).

4) Sphalerite-galena-bismuthinite

This assemblage of minerals is rather rarely found in Rangpo and PachiKhani copper deposits. Small grains of bismuthinite occur at the sphalerite-gangue and galena-gangue contacts. Bismuthinite may be placed as younger to both sphalerite and galena in age. The intrusion of bold advancing face of galena into sphalerite indicates that the former is younger in age to the latter.

Among the supergene oxide minerals, associated with copper ores, malachite is found in cavities, open spaces and vein fillings in the ores. It is sometimes derived from chalcocite. In highly oxidised ores, veins of limonite appear in malachite. Azurite, which is rarely found, occurs in the form of veins in malachite. Malachite is, therefore, younger to chalcocite, and older to azurite and *limonite* in age.

The gangue minerals include quartz, biotite, chlorite, sericite, garnet and carbonates, all of which are found to be partly replaced by the sulphide minerals. A second generation of quartz occurs in the form of veins traversing all the ore minerals.

Associated with lead-zinc occurrences :

Galena-sphalerite ores

This is the only mineral assemblage found in lead-zinc ores and is composed mainly of galena with sporadic sphalerite.

Grains of sphalerite occur within galena as well as at the gangue-galena contact. Sometimes sphalerite has a few small grains of pyrite. The partial replacement of sphalerite by galena is very evident from their textural relationship showing wavy contact and the presence of veins of galena in sphalerite. Therefore, galena is definitely younger to sphalerite in age. Thin veins of galena along the cleavage and the intragranular spaces of the gangue minerals are very common.

Anglesite is the most common among the supergene lead minerals associated with galena. Others, which occur in the fractures, veins, vugs and open spaces in galena and sphalerite include cerussite, rozenite, dundasite, pyromorphite and mimetite. Quartz, calcite and dolomite are the common gangue minerals associated with this assemblage of ores.

Paragenesis

The study of textural relations of the ore-minerals thus provides with a fair idea of their paragenetic sequence. Since there has been two phases of hydrothermal mineralization, the paragenesis of the earlier, Cu-Fe sulphides, and the later, Pb-Zn sulphides have been presented separately. The sequence of the identified hypogene ore-minerals and the supergene minerals such as covellite, chalcicite, enargite, malachite, azurite and limonite appear to be normal as far as their order of formation is concerned.

The paragenesis of the ore minerals are presented in the table 15.

TABLE - 15 Paragenesis of the sulphide ore deposits encountered in the Darjeeling Himalayas.

Minerals	Time of mineralization	
First phase of mineralization		
Arsenopyrite	———	
Pyrrhotite	———	
Pyrite	———	
Chalcopyrite	———	
Sphalerite	... —	
Galena	—	
Bismuthinite	—?—	
Enargite		—
Covellite		— ...
Chalcocite		— ———
Malachite		—
Azurite		—
Limonite		———
Second phase of mineralization		
Pyrite	—	
Sphalerite	———	
Galena	———	
	Hypogene	Supergene

Chapter VII

DISTRIBUTION TRENDS OF TRACE ELEMENTS IN THE HOST ROCKS AND ORE-MINERALS

The distribution of some 16-20 trace elements in the ore zone rocks, altered and unaltered host rocks of Cu, Pb and Zn deposits and their important hypogene and supergene minerals is a subject matter of this study. Fresh rock samples were collected systematically not only from the ore zones of the base metal deposits but also from their host rocks at certain regular intervals in the field. Only the selected samples have been taken into consideration for the present discussion. Some of the ore-minerals were separated by Isodynamic magnetic separator and some others, by hand picking. The samples were analyzed spectrographically for determining quantitatively the trace elements which may have some significance in the present study.

The trace element abundances in the rocks occurring within the copper and lead-zinc deposits and in the respective host rocks have been presented in the tables 16 and 17. The ppm values of concentration of the trace elements determined in the ore minerals has been presented separately in the tables 16 and 17 and Figs. 24 and 25.

For comparing conveniently the relative abundances of various trace elements in the different rocks, the following arbitrary scale

of concentration of elements has been adopted :

PPM values	Scale symbol	Concentration
5000	EH	(Exceptionally high)
1000 - 5000	VH	(Very high)
500 - 1000	H	(High)
100 - 500	M	(Moderate)
50 - 100	L	(Low)
10 - 50	T	(Trace)
2 - 10	ST	(Slight trace)
0 - 2	A	(Absent)
	ND	(Not determined)

I. Distribution of trace elements in the host rocks

a) Associated with copper deposits (Figs. 19 & 20, 21, Tables 16,17,29 to 36).

The presence of Zr, V, Ni, Ag, Zn and Pb in the range, moderate to traces, has always been recorded from the ore zone through altered to unaltered rocks. The concentrations of Sr, Ti, Cr and As gradually decrease from the ore zone to unaltered rocks. Ga, Ge, Sn and Bi are characteristically absent in the unaltered rocks but their presence in low concentration or traces have been detected in the ore zone as well as in the adjacent altered rocks. Mo, which has moderate to very high concentration in the unaltered rocks appears to have been depleted or reduced to traces in the altered rocks as also in the neighbouring ore zone.

The distribution trends of the elements like Sr, Ti, Cr, Pb, Zn, As and Bi in the ore zone and the adjacent altered wall rocks provide important evidences for not only their introduction by the

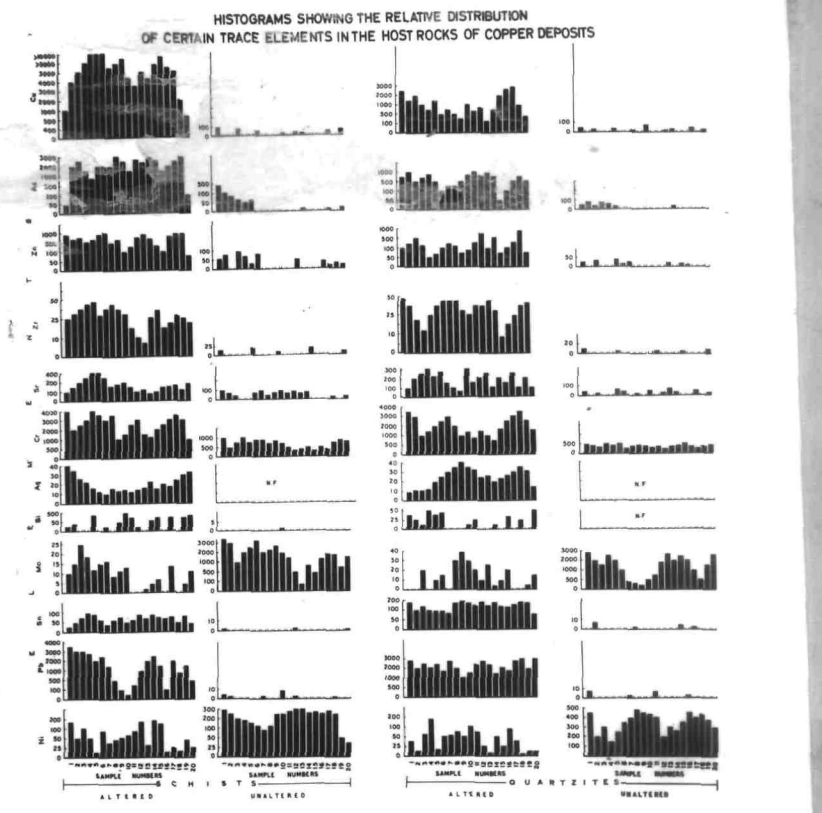
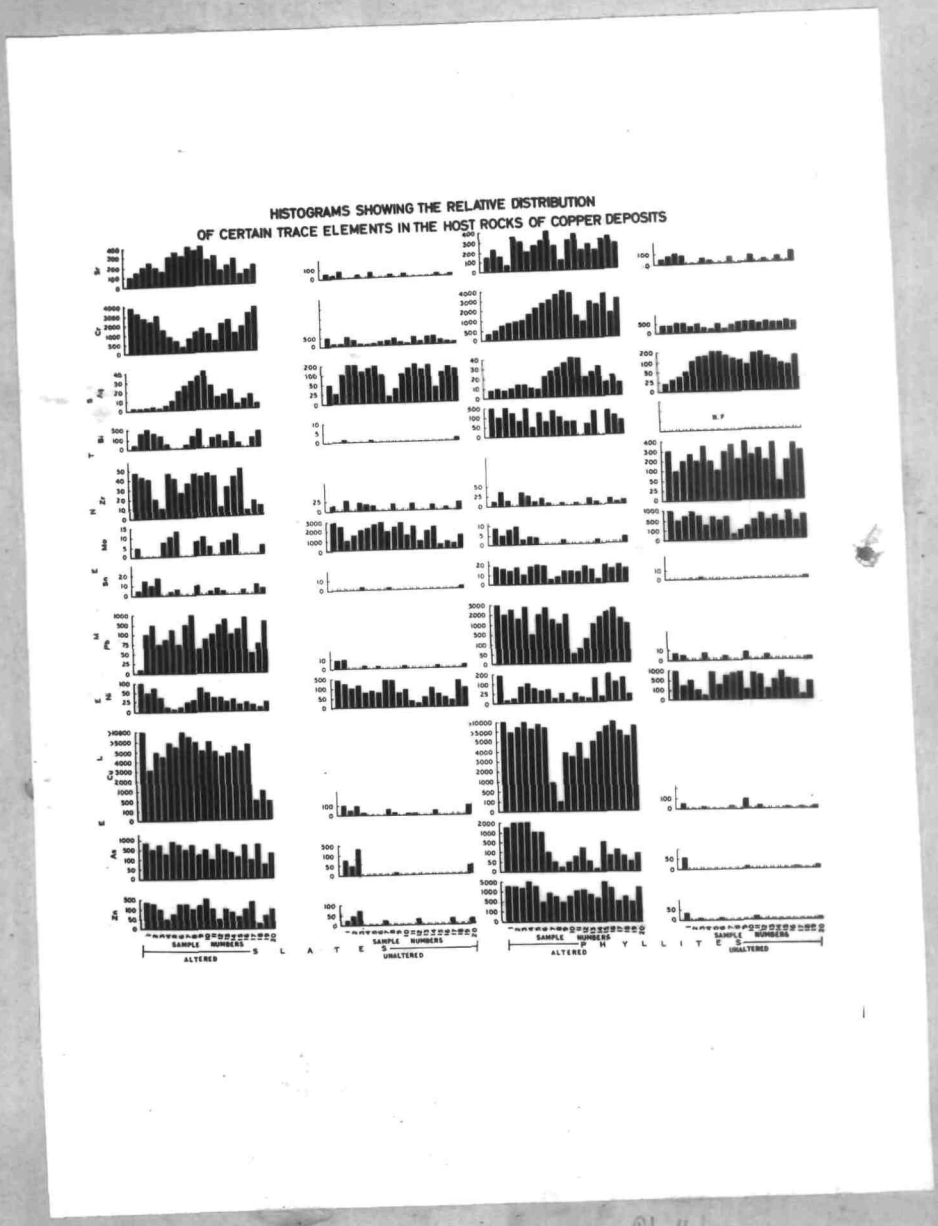

HISTOGRAMS SHOWING THE RELATIVE DISTRIBUTION
OF CERTAIN TRACE ELEMENTS IN THE HOST ROCKS OF COPPER DEPOSITS
SAMPLE NUMBERS
SCHISTS
ALTERED
UNALTERED
QUARTZITES
ALTERED
UNALTERED

Fig. 19



Slate

Phyllites

Fig. 20

TABLE - 16 Comparison of trace elements concentration in the host rocks of copper, lead and zinc deposits.

Elements	COPPER DEPOSIT			LEAD-ZINC DEPOSIT		
	Ore zone rocks	Altered Rocks	Unaltered rocks	Ore zone rocks	Altered rocks	Unaltered rocks
Sr	M	L	T	M	T	ST
Ba	ND	ND	ND	H-VH	M	VH
Ti	EH	VH	M	T	H-VH	VH
Zr	T	T	T	ND	ND	ND
V	T	T	M	T	L	M
Cr	VH	H	M	VH	H	H
Mo	T	T	M-VH	M	L	T
Co	ND	ND	ND	T	T	L
Ni	M	L	M	M	L-M	VH
Cu	-	M	T	T	T	T
Ag	T	ST	L-M	T	S T	H-VH
Zn	M	M	T	-	ST (?)	ST
Cd	-	-	-	EH	ST	A
K_2O	T	ST	A	ST	A	A
In	-	-	-	ST	A	A
Ge	T	T	A	ST	A	A
Sn	L	T	A	T	A	A
Pb	M	L	T	-	ST	ST
As	H	M	T	H	ST-T	ST
Sb	ND	ND	ND	T	ST	A
Bi	M	L-ST	A	T	ST	A

TABLE - 17 Comparison of trace element concentration in hypogene and supergene sulphide ore minerals

Elements	HYPOGENE MINERALS						SUPERGENE MINERALS							
	COPPER DEPOSITS (A)			LEAD-ZINC DEPOSITS (B)			COPPER DEPOSITS (A)		LEAD-ZINC DEPOSITS (B)					
	Pyrite	Chalcopyrite	Pyrrhotite	Pyrite	Galena	Sphalerite	Limonite	Malachite	Limonite	Malachite	Anglesite	Cerussite	Pyromorphite	Rozenite
Co	20-300	90-210	110-125	10- 40	2-5	2-8	< 100	NF	< 100	NF	ND	NF	NF	100
Ni	5-100	100-500	215-275	5- 8	5-10	10-55	300->500	20 - 50	NF	300	ND	NF	NF	80
Ag	5-20	3-8	6-8	5-10	3-10	4-10	< 2- 150	100-200	200- 500	50	800->1000	20	850	NF
Pb	5-25	25->10000	100-210	5-15	-	-	50- 5000	800->1000	3000->8000	> 1000	>10,000	> 10,000	> 10,000	500
Sn	5-10	5- 10	8-10	5-10	3-10	6- 9	200	50	100- 200	NF	60- 100	2	NF	NF
Cd	10-40	5-10	6- 8	10-50	10-300	3300->10,000	300-< 500	NF	200-500	NF	20- 50	2	NF	NF
Sr	10-100	NF	NF	10-90	NF	NF	30- 150	ND	< 100	ND	100- 150	NF	NF	NF
V	10- 80	60-150	30 - 45	30-65	2- 15	2- 10	ND	ND	ND	ND	ND	NF	80	NF
Mo	10-100	30-100	25- 30	20-100	2- 5	2- 3	ND	ND	ND	ND	ND	NF	1000	NF
Ti	20-500	90-160	100-130	80-500	10-130	10-70	450- > 1000	40-50	1200- > 2000	100	ND	NF	1000	NF
Cu	5-15	-	-	5- 10	10-20	8-30	50-> 5000	> 8500	1500- > 5000	> 5000	35- 150	400	80	75
Zn	3-15	25-500	40-100	5- 15	-	-	50-> 5000	> 1000	2500- > 5000	1000	<400->800	500	NF	> 2,000
Cr	10-50	NF	NF	10- 30	NF	NF	50- 150	ND	100- 400	ND	ND	NF	> 7000	NF
As	500->10000	80-150	70-80	1350->10000	4-50	4-20	100- 1500	ND	300- 1000	ND	400- 500	NF	300	200
Sb	5- 100	10-25	70-80	6- 100	3-10	5-80	5-> 500	100	100 - 200	100	> 100- < 200	NF	400	6
Bi	3-25	10-50	8-10	2-10	4-9	NF	ND	ND	ND	ND	80 - 90	NF	NF	NF
Au	SL	NG	NG	NG	NF	NF	ND	ND	ND	ND	ND	NF	NF	NF
Ba	NF	ND	NF	NF	5-18	8 - 60	< 20-400	10 - 20	300-600	50	50-60	45	500	NF
In	NF	NF	NF	NF	4	4 -9	ND	ND	ND	ND	ND	ND	ND	ND
Gr	NF	NF	NF	NF	NF	4-30	ND	ND	ND	ND	ND	ND	ND	ND
Ga	NF	NF	NF	NF	NF	3-9	ND	ND	ND	ND	ND	ND	ND	ND

SL = Slightly higher
NG = Negligible
ND = Not detected
NF = Not found

mineralising solutions in the ore zone but also for their restricted permeation into the adjacent wall rocks. They have therefore, been considered as index trace elements which may have genetic association with the copper ore deposits of the study area.

b) Associated with lead-zinc deposits (Figs. 22 & 23, Tables 16,17, 27 & 28.

The elements namely Sr, V, Mo, Co, Cu, generally have concentrations, moderate to traces, in the ore zones as well as in the host rocks. The concentration trends of Cr, Cd and As decrease from the ore zone through the altered to unaltered rocks. The unaltered rocks record relatively higher concentrations of Ba, Ti, V, Ni, and Ag than in either altered or ore zone rocks. Ga, In, Ge and Sn are present in traces to slight traces in the ore zone rocks but they are completely absent in the altered and unaltered rocks. Sb and Bi are absent in the unaltered rocks but their presence in slight traces and traces were detected in the altered rocks and the ore zone respectively.

From a study of the concentration trends of Sr, Cr, Mo, Cd, Ga, In, Ge, Sn, As, Sb and Bi in the ore zone and the altered rocks it may be inferred that the elements were introduced in the ore zone by the invading mineralizers, a part of which also diffused into the adjacent altered wall-rocks where some of these elements are also present but in relatively low concentrations.

Conclusion

A comparison between the concentration trends of trace elements in the ore zone of copper and that of lead-zinc deposits, leads to the

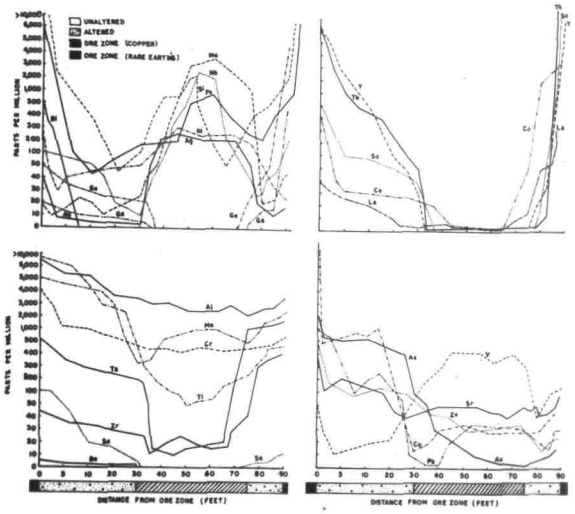


FIG. DISTRIBUTION OF MINOR ELEMENTS
IN THE UNALTERED AND ALTERED WALLROCKS
AT THE COPPER DEPOSITS, SIKHIP AREA

Fig. 21

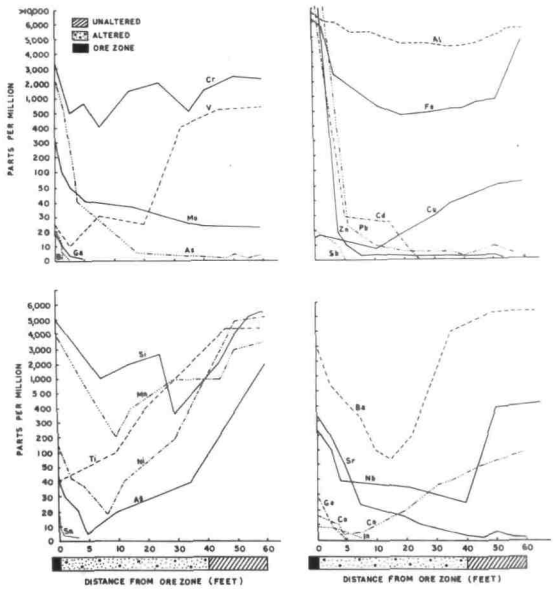
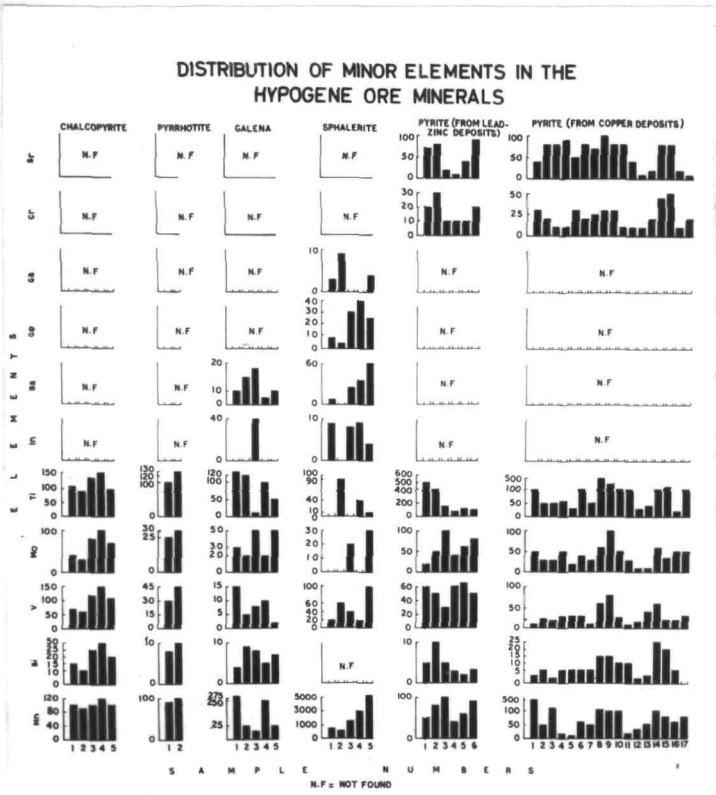


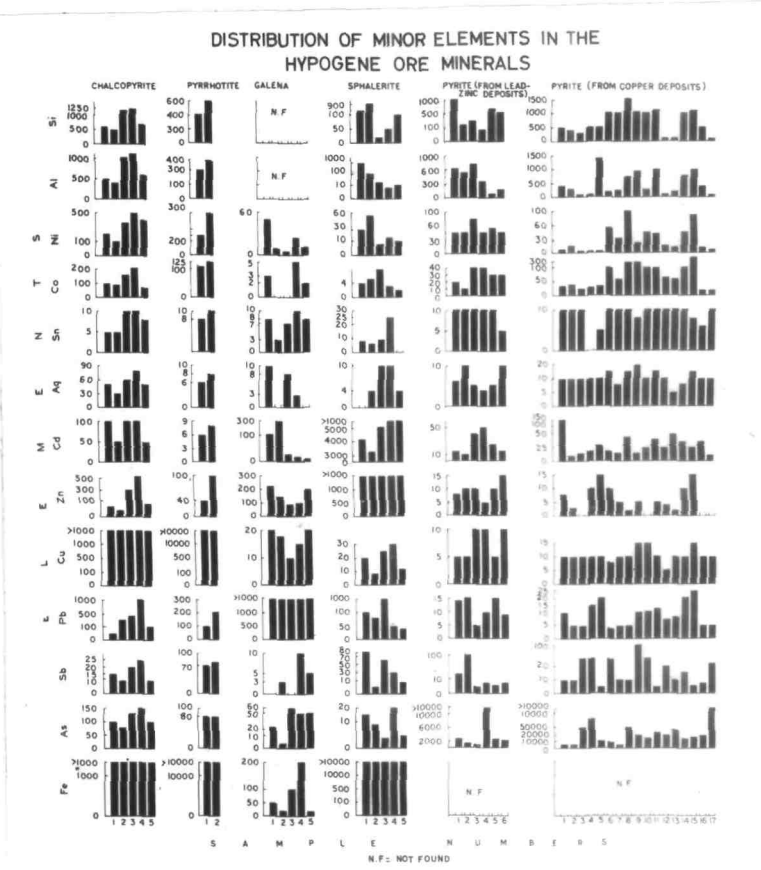
FIG. DISTRIBUTION OF MINOR ELEMENTS
IN THE UNALTERED AND ALTERED WALLROCKS
AT THE LEAD-ZINC DEPOSITS RISHI AREA

Fig. 22


DISTRIBUTION OF MINOR ELEMENTS IN THE HYPOGENE ORE MINERALS
CHALCOPYRITE
PYRRHOTITE
GALENA
SPHALERITE
PYRITE (FROM LEAD-ZINC DEPOSITS)
PYRITE (FROM COPPER DEPOSITS)
ELEMENTS
Sr
Cr
Ga
Ge
Ba
In
Ti
Mo
V
Bi
Mn
N.F
SAMPLE NUMBERS
N.F = NOT FOUND

a

Fig. 24


DISTRIBUTION OF MINOR ELEMENTS IN THE HYPOGENE ORE MINERALS
CHALCOPYRITE
PYRRHOTITE
GALENA
SPHALERITE
PYRITE (FROM LEAD-ZINC DEPOSITS)
PYRITE (FROM COPPER DEPOSITS)
MINOR ELEMENTS
Si
Al
Ni
Co
Sn
Ag
Cd
Zn
Cu
Pb
Sb
As
Fe
N.F
SAMPLE NUMBERS
N.F = NOT FOUND

b

following conclusions:

1) Sr, V, Cr, Ni, Ag and As have more or less similar trends of concentration.

2) In both the ore zones Ga, In, Ge and Sn are present although their concentrations are very low.

3) Tl is exceptionally high in the copper ore zone whereas the lead-zinc ore zones have a trace of it.

4) The lead-zinc deposits have exceptionally high concentration of Cd whereas it is insignificant in the copper ore zone.

5) The concentration of Mo in lead-zinc deposit is higher than in copper deposit and the order of abundance of Bi is reversed in these two ore deposits.

6) Some of the trace elements, which frequently occur in the ore zones and their respective altered wall-rocks, are typically absent in the unaltered host rocks.

Since the majority of these trace elements indicate a more or less comparable abundance in the two ore zones, it is reasonable to conclude that the two kinds of sulphide deposits are related genetically.

II. Distribution of trace elements in ore-minerals

a) Hypogene ore minerals (Tables 17, 46, 47, 49, 50, 51; Fig. 24)

Such hypogene minerals as pyrite, chalcopyrite and pyrrhotite, which commonly occur in the copper ore deposits, and as pyrite, galena

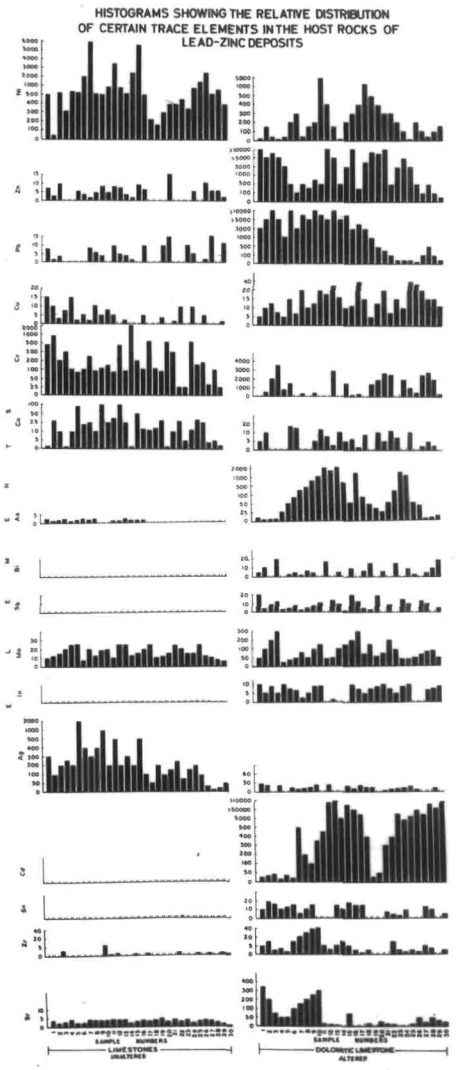

HISTOGRAMS SHOWING THE RELATIVE DISTRIBUTION
OF CERTAIN TRACE ELEMENTS IN THE HOST ROCKS OF
LEAD-ZINC DEPOSITS
SAMPLE NUMBERS
LIMESTONES
UNALTERED
SAMPLE NUMBERS
DOLOMITIC LIMESTONE
ALTERED

Fig. 23

and sphalerite, that largely compose the Pb-Zn deposits, have been selected for their trace element studies. Pyrite is common to both the deposits.

The trace element distribution in the pyrites, that are associated with the copper ores and the lead-zinc ores, presents some interesting facts which have great genetic significance. They are as follows:

1) The relative abundances of Ag, Pb, Ti, Cu, Zn, Cr, As and Bi in them are strikingly the same.

2) In pyrites from both the deposits, As has a wide concentration range.

3) Ag, Pb, Cu, Zn and Bi occur in minor traces.

4) Cr has low concentration but it is slightly more abundant than Ag, Pb, Zn, etc. in the pyrites belonging to both the deposits.

The distribution of the trace elements in the ore minerals like chalcopyrite, pyrrhotite, galena and sphalerite shows that with the exception of Ag and Sn, which occur uniformly in slight traces in all these four minerals, most of the other elements have much more higher concentration in chalcopyrite and pyrrhotite, than in galena and sphalerite. This holds good particularly in the cases of Co, Ni, V, Mo, Ti and As.

b) <u>Supergene minerals</u> (Tables 17, 43, 44, 45 & 48; Fig. 25)

Limonite, malachite, anglesite, cerussite, pyromorphite and

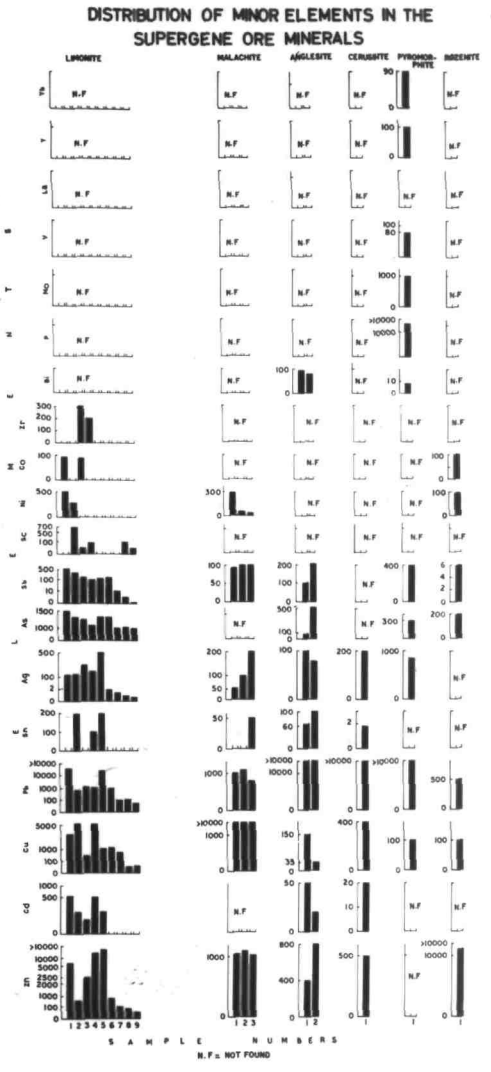

DISTRIBUTION OF MINOR ELEMENTS IN THE SUPERGENE ORE MINERALS
LIMONITE
MALACHITE
ANGLESITE
CERUSSITE
PYROMORPHITE
INDENITE
ELEMENTS
Yb
Y
La
V
Mo
P
Bi
Zr
Co
Ni
Sc
Sb
As
Ag
Sn
Pb
Cu
Cd
Zn
N.F
SAMPLE NUMBERS
N.F = NOT FOUND

Fig. 25

rozenite are the supergene minerals which have been selected for their trace element studies. Among these minerals, limonite and malachite are common to copper and lead-zinc deposits, and the rest occur in the Pb-Zn deposits.

A comparison of the trace element distribution between the limonites from the copper and those from the lead-zinc deposits shows that generally Pb, Ti, Cu, Zn and As have highest concentrations. Next in abundance in limonites from both the deposits are Sn, Cd, Cr, Sb and Ba. Co recorded values less than 100 ppm in the limonites belonging to both the deposits. Ni which is significantly high (300- 500 ppm) in the limonites from copper deposits, has not been found in the limonites from lead-zinc deposit. However, the higher concentration of certain elements may partly be attributed to limonite and partly to certain minor mineral inclusion in the limonite.

A striking feature of the malachites, which are common to both the deposits, is that they have considerably high concentrations upto $\geq$1000 ppm of Pb and Zn.

With the exception of Pb and Zn, the distribution of other trace elements in anglesite, cerussite, pyromorphite and rozenite do not bear any significant relation as far as their abundances are concerned. Only pyromorphite has abnormally high concentration of Ag, Mo, Ti and Cr.

Chapter VIII

WALL-ROCK ALTERATION AND PROBABLE SOURCE AND NATURE OF MINERALISATION

Wall-rock alteration

It is very well known that the study of hydrothermal alteration of the wall-rocks of ore deposits has a great significance in metallogenesis. When hydrothermal solutions bring about some mineralogical, chemical and physical changes in the wall-rocks around an ore body, it becomes necessary to study the extent and nature of alteration, which is often a complex process. When properly interpreted, the study may give an idea regarding the source and nature of ore solution, in addition to the chemical process involved in the formation of the ore as well as the associated new minerals. Moreover, it may also serve as a guide to locate ore deposits of hydrothermal origin. There are many instances in which wall-rock alteration has proved to be a valuable tool in mineral exploration because the altered zones are usually more conspicuous than the ore bodies. It may be of interest to note here that in course of the present investigation, the author has been able to locate a number of new occurrences of sulphide ores in the Eastern Himalayas applying the knowledge of wall-rock alteration as a very useful guide. Several eminent workers such as Hewett (1928), Lindgren (1933), Lovering (1949), McKinstry (1948), Sales and Mayer (1949, 1950), Anderson (1949), Ohle (1951),

Schwartz (1955, 1959), Bateman (1959), Gawad and Ker (1959), Park Jr. and MacDiarmid (1964) and many others have dealt adequately with the wall-rock alteration and its importance in ore geology. According to Lovering (1949) the hydrothermal alteration associated with ore deposits is contemporaneous with ore deposition and that the different mineralogical zones in the ore bodies and the surrounding country rocks are just like the reaction rims representing the diminishing activity of the powerful solutions that deposited the ore.

None of the earlier workers, who reported and described several occurrences of sulphide ore deposits from the study area or from any other region in the Eastern Himalayas, have stated anything about the pattern or nature of wall-rock alteration. An attempt has, therefore, been made to study carefully the wall-rock zones in the vicinity of some sulphide ore deposits in the Eastern Himalayas.

I. Alteration associated with the lead-zinc ore bodies in carbonate host rocks :

The silicified dolomitic limestones are the wall-rocks of lead-zinc deposits of Rishi area. The unaltered portions of the country rocks are represented by massive limestones.

The nature and sequence of alteration of the wall-rocks and their paragenetic relation with the ores have been determined from their petrological studies. They are presented as below :

Dolomitization
Silicification
Lead-Zinc Mineralization

The mineralisation is strictly confined to the dolomitized zones. The areas of alteration are sporadic. Generally, the change from limestone to dolomitic limestones appears to be abrupt. As a result of hydrothermal activity the limestones have undergone distinct and well-marked changes, as given below:

A. Physical changes due to alteration

1. Dolomitization

Changes in colour and texture of limestone due to dolomitization are easily discrenible. Increase in porosity and permeability of the rock is distinct. Fracturing of mineral grains is a common feature.

Colour

The unaltered limestones of the study area are dark grey in colour while the altered dolomitic limestones show invariably cream or dirty white colour. Generally, the change of colour is gradational with a transitional zone of light grey coloured limestones having clusteres of dolomite. Sometimes, however, the contacts between the unaltered and altered rocks are sharp. Hewett (1928), Watson (1905), Lovering (1949) and Park Jr. and MacDiarmid (1964) have recognised such a change from darker to lighter shades of grey colour during

hydrothermal activity on limestones. It is believed that the dark-coloured carbonate rocks undergoing hydrothermal alteration develop a tendency to expel impurities such as carbon and due to which the altered rocks become white or light grey in colour.

Texture

The alteration of fine-grained or micritic limestone of the area is always accompanied by a notable increase in grain size, producing thereby the medium grained varieties of dolomitic limestones. Presence of some unusually large sized isolated dolomite crystals within the smaller calcite grains is a striking feature of these dolomitic limestone. Some of the dolomite grains have grown upto a size of 5 or 6 mm in diameter. The grains are characteristically idiotopic in texture. Such changes in texture and grain size of the rocks in the altered zones as compared to those in the unaltered zone are remarkable. The contact between the fine-grained or micritic unaltered limestones and the altered dolomitic limestones is generally sharp. Sometimes a transitional zone comprised of a fine-grained dolomitic limestone was also encountered. In the field it is rather difficult to distinguish between them by their textural characters. One has to depend much on their petrographic characters, which are much more diagnostic. To some extent, however, the grey and light grey colour is defined, but that alone cannot be taken as a reliable criterion. Porphyrotopic texture is a common feature of the altered rock. The porphyrotopes of fresh and clear dolomite euhedra occur in a groundmass of fine-grained calcite which is always dusty, dull and

clouded. The normal size of the dolomite porphyrotopes varies from 1.6 mm to 2.8 mm in diameter.

The alteration of limestones to dolomitic limestones is thus a case of progressive change. The increase in grain size of dolomite is proportional to the increase in the content of dolomite, and thus it reflects the intensity of dolomitization to which the rocks were subjected. Such textural peculiarities have been reported from many parts of the world. Ohle (1951) stated "As recrystallisation proceeds, the average grain size increases and also the percentage of the total carbonate that is dolomite". He defined the hydrothermal dolomites as recrystalline. Rasul and Ali (1968) have recorded an increase in grain size as well as a change of colour of dolomites hosting the sulphide ore deposits from Bageshwar area in Almora district of Kumaon Himalayas. Similarly, Lovering (1949) and Schwartz (1959) have also observed increase in the grain size of carbonate rocks through dolomitization. As reported by Tarr (1936) and Ridge (1936) the hydrothermally affected dolomites are always found to be more coarsely textured than the unaltered dolomitic limestones. Hewett (1928) in his classic work reported similar variation in texture around the hydrothermal ore deposits of North America and Europe. Jicha Jr. (1951) reported abnormally large-sized crystals of hydrothermal dolomite increasing upto 1 cm in diameter from the lead-zinc deposits of Cave di Pradoe, in the Alps.

Porosity, permeability and fracturing

It is now believed that an increase in porosity is related to the dolomitization of the rock. Pinckney and Rye (1972) studied the alteration pattern around the Mississippian limestone wall-rocks, and have found an increase in the porosity of rocks in the dolomitized zone. A comparative study of the petrographic and textural characters of the altered and unaltered carbonate rocks of the study area was made in order to determine the nature of physical and mineralogical changes in the altered rocks. Fracturing and jointing are the characteristics of most of the altered carbonate rocks within which there are innumerable vugs. Such features are typically absent from the unaltered rocks. The dolomitized carbonate rocks have porphyrotopes of dolomite that occur in clusters and are highly fractured. All such features like micro-vugs, fractures, etc., are rarely found in the unaltered rocks. The porous and vuggy dolomites thus became favourable receptacles for the ore deposits. Martin (1958) has supported the view of Currier (1935), and has suggested a relation between alteration and the loss of competency. Landes (1946) stated that "an increase in porosity is related to dolomitization." He interpreted this increase as a result of leaching (decalcification or dolomitization) and recrystallisation during the process of replacement. Further, Landes (op.cit) stated that the conversion of calcite to dolomite occurs molecule by molecule by the substitution of magnesium carbonate for part of the calcium carbonate, causing thereby reduction in volume and increase in

porosity. However, Hewett (1928) has a different opinion and observes no increase in volume. Hewett (op. cit.) in his classic work on the alteration of carbonate rocks further puts forward that dolomitized limestones near ore deposits are commonly slightly porous but the porosity is rarely more than 5 per cent.

An increase in porosity and permeability of the carbonate rocks through dolomitization was also supported by Tarr (1936), who believed that the hydrothermal dolomites are more porous than their unaltered counterparts. Ohle (1951) suggested that the high percentage and coarse granularity of dolomite may be responsible for an intense increase of the permeability of limestones. He calculated the increase in permeability of over 18,000 per cent in the carbonate rocks due to dolomitization. In his important paper on the origin of porosity in the carbonate rocks, Murray (1960) has given petrographic evidence for the relationship between porosity and dolomitization.

2. Silicification

The minor openings such as vugs and micro-fractures of the dolomitic limestones were later invaded by silica in the form of jasperoid which has also partly replaced both calcite and dolomite. This resulted in the silicification of some dolomites. Relics of calcite and dolomite crystals have occasionally been found in the silicified zones of the rocks. The rugged and irregular contacts between calcite and jasperoid or dolomite and jasperoid, also show the eating away phenomena.

Rhomboidal pseudomorphs of jasperiod after dolomite are of common occurrence. The textural relation between the ore minerals and jasperoid indicates that the invasion of ore solutions followed the silicification. Two varieties of silica are commonly found, (1) grey fine-grained jasperoid replacing the carbonates, (2) white, semi-vitreous and coarse grained quartz occurring in vugs, voids and micro-veins. The deposition of ore is associated with the first type of silica. These two varieties of silica possibly belong to two different generations. According to Parks Jr. and MacDiamid (1964), silicification is abundant in the hydrothermal deposits, and the silica may be introduced by hydrothermal fluids. They believe that one of the prevalent features of the epigenetic silica deposits of hydrothermal origin is jasperoid. According to them (op.cit.), "This process of silicification is one form of ground preparation, whereby soft, impermeable and unfavourable rocks are made more competent and more receptive to the introduction of fluids and the deposition of ores".

Pinckney and Rye (1972) reported that, "Mississippian limestone wall-rocks surrounding a low-temperature ore body in the Hicks dome area of southern Illinois were dolomitized, recrystallised and silicified." They believe that the hydrothermal activity produced these alteration effects at low temperatures.

The silicified wall-rocks in the work area are very hard and competent, and at places even the interbedded thin intercalations of shales clearly show the effects of silicification. The /shales, which are

ordinarily impermeable and not very receptive to ore-bearing fluids had been rendered hard and somewhat brittle through silicification.

B. Mineralogical changes due to alteration

The mineralogical changes in the altered carbonate rocks are very distinct. Dolomite, calcite and talc are the chief minerals involved in this change (Fig. 26).

The following changes in the mineralogical composition of the rocks have been observed (Table 18).

TABLE - 18 Average composition of carbonate rocks

Minerals	Unaltered rocks (Limestones) Average of 12 samples	Altered rocks (Dolomitic limestones) Average of 10 samples
Dolomite	1 - 10 %	80 - 90 %
Calcite	80 - 90 %	5 - 10 %
Talc	Nil	Restricted to the mineralized zones with an average of 0 - 4%.

The altered rocks with a large percentage of dolomite are characteristically idiotopic and coarsely crystalline. Talc, being associated only with the altered rocks[5], has been considered to be a mineral of hydrothermal origin (Lindgren, 1933; Park Jr. and MacDiarmid, 1964). The contrasting percentage of dolomite and calcite is rather very characteristic. It may be noted here that in the altered rocks (dolomitic limestones) dolomite is the most predominating mineral (80-90%), and calcite, which has been replaced by dolomite, is reduced to about 5 to 10% in the altered rocks (Table 18). On the other hand the order of percentage composition of dolomite and calcite is almost reversed in the unaltered limestones(Table 18).

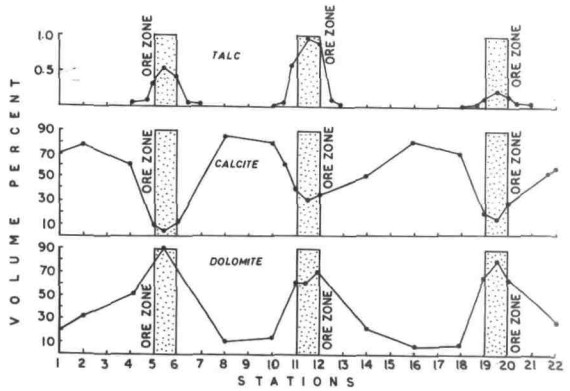


FIG. VARIATION DIAGRAM SHOWING CHANGES IN MINERALOGICAL COMPOSITION DUE TO WALLROCK ALTERATION AT LEAD-ZINC DEPOSIT RISHI AREA

Fig. 26

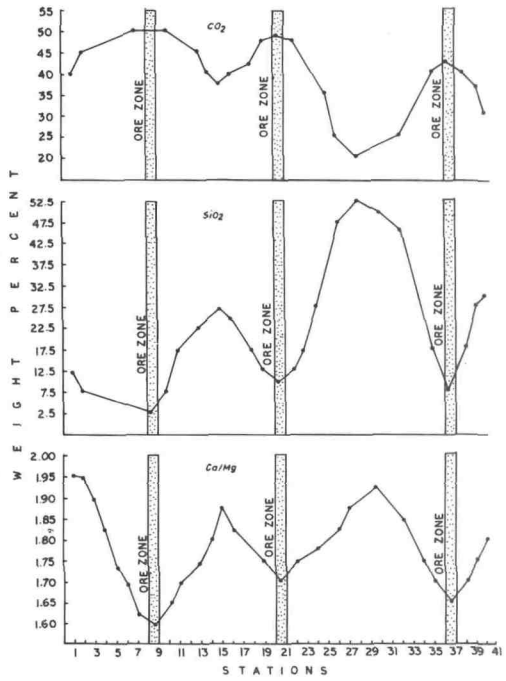


FIG. VARIATION DIAGRAM SHOWING CHEMICAL CHANGES DUE TO WALLROCK ALTERATION AT LEAD-ZINC DEPOSIT RISHI AREA

Fig.27

C. Chemical changes due to alteration

In the area under investigation, major chemical constituents of the country rocks increase or decrease quantitatively from the highly altered zone through partly altered to the unaltered zone. The proportions in which Ca/Mg, SiO_2 and CO_2 occur and vary from one locality to the other have been shown in the variation diagram (Fig.27).

TABLE - 19 Average composition of the altered and unaltered carbonate rocks*

Major chemical constituents	Altered rocks (quantity in per cent)	Unaltered rocks (quantity in per cent
CaO	26.55	47.45
MgO	18.24	1.25
CaO/MgO	1.40	36.36
Ca	15.1	21.76
Mg	14.2	11.94
Ca/Mg	1.08	1.82
CO_2	45.27	34.25
SiO_2	12.30	31.30
R_2O_3	1.77	2.64
Ins.	9.70	22.54

* Average of 40 samples

Ca/Mg distribution

It is clear from the variation diagram (Fig. 27) that the Ca/Mg ratio varies from 1.60 to 1.70 as shown at station Nos. 8-9, 20-21 and 36-37. The progressive decrease in the values of Ca/Mg ratio obviously indicates an increase in the dolomite content of the wall-rocks

towards the ore body.

SiO_2 distribution

The variation diagram (Fig. 27) shows an interesting pattern of SiO_2 distribution. A progressive decrease in the value of SiO_2 content towards the ore bodies is marked by a progressive decrease of CaO/MgO content. The SiO_2 in the ore zones varies between 2.5 and 12.5 with a maximum of 52.5 in the unaltered limestones.

CO_2 distribution

The CO_2 content (Fig. 27) has an important quantitative relation with that of SiO_2. The increase in CO_2 is marked with a corresponding decrease in SiO_2 and vice versa. The CO_2 content in the ore bodies varies from 43 per cent to 50 per cent.

Indication of zoning

The mineralogical and chemical variations in the altered and unaltered rocks clearly indicate the presence of a well-marked zoning in the carbonate rocks around the lead-zinc deposits of Rishi area.

II. Alteration associated with the copper ore bodies in metamorphic host rocks

The low grade metamorphic rocks such as phyllites, schists, slates and quartzites of the Daling and Baxa Series have hosted the copper ores. The wall rocks of copper have been intensively chloritized and sericitised. Auden (1935) who took long traverses in the Eastern Himalayas upto Tibet, reported about the high order of chloritisation and sericitisation of these rocks.

Alteration zones adjacent to massive sulphide deposits in metamorphic rocks are commonly difficult to distinguish from regionally metamorphosed country rock, particularly in the greenschist facies (Anderson, 1949). According to Hemley and Jones (1964) "the pressure-temperature conditions controlling the origin of mineral assemblages developed in hydrothermal alteration probably range from typical hot-spring conditions to the upper pressure-temperature limits of green-schist grade metamorphism". Sericite and/or chlorite are the minerals common in both the greenshist facies and alteration zones adjacent to the massive sulphide deposits. According to Anderson (1949), "If this mineral assemblage is limited in extent, is envelope like and transects original lithologic units or is conformable to these units, alteration zones are indicated". Anderson (1949) believes that chlorite is present in appreciable volumes in the rocks adjacent to some massive sulphide deposits, and Fe and Mg metasomatism related to ore deposition is usually accepted as the reason for its presence. In the Rouyn-Noranda area in Quebec, chlorite-rich rocks associated with some sericite and secondary quartz form pipelike alteration zones in rhyolite, is as much as 300 feet in diameter (Dugas, 1966). Widespread chloritisation is common on the foot wall of the United Verde massive sulphide pipe (Jerome, Arizona), and quartz porphyry was converted partly or wholly into chlorite, indicating large-scale Fe and Mg metasomatism (Anderson and Creasey, 1958). The Coeur d' Alene district in northern Idaho, one of the largest lead-zinc-silver deposits in the world, is an excellent example of development of sericite as one of the few persistently stable minerals in the alteration

halo, representing the conditions of hydrothermal mineralisation (Park Jr. and MacDiarmid, 1964). Wall-rock alteration with sericitization and silicification accompanied the deposition of base metal ores in the Magma Mine, Arizona. It was most intensely developed in the diabase sills, but has also affected schists and clastic sediments (Short et al., 1943).

A. Physical changes due to alteration

The following are the physical changes that have been recorded in the metamorphic rocks of the work area due to hydrothermal alteration:

Colour

The bleaching effect due to the hydrothermal alteration is most conspicuous in these rocks which often show a change in colour from dark grey to light grey or white. According to Wilson (1941) such changes are related to hydrothermal alteration and the altered rocks are commonly bleached; and light coloured minerals like sericite, quartz carbonates, etc. appear. The change in colour due to bleaching has been noticed in most of the disseminated copper deposits throughout the world. For example, at Cananea, Mexico, where the rocks have been bleached to a very light grey or white colour during intense sericitization. Anderson (1947), while describing the epithermal mineralization at Last Chance and Hornsilver Mines, Lava Creek district, Butte county, Idaho, has furnished an excellent example of bleaching of dark coloured igneous rocks, forming a broad zone of light grey sericitic rock. According to Howie (1924) the granodiorites and diabase at Grass valley, California, have been bleached to such an extent that they have almost

lost their identity. Exceptions to such colour changes where dark coloured rocks are produced have also been reported by Knopf (1931), Park and Cannon (1943), James (1949) and Schwartz (1959). But such exceptions are very rare.

In the study area the wall rocks adjacent to ore bodies show a distinct change in colour. The altered rocks show various shades of green colour due to the formation of chlorite and biotite. The progressive change in colour from dark grey to green is due to development of chlorite and then it becomes greyish white as chlorite has been gradually replaced by sericite. Silicification may also be partly held responsible for adding some light coloured areas in the altered zones.

Texture

The alteration has also brought about a change in texture of the wall rocks in which an increase in the grain size of almost all the minerals constituents is a common feature. The altered rocks are characteristically coarse grained and roughly schistose. Even the accessory minerals such as quartz, chlorite, biotite, muscovite, etc. have grown in size. Quartz has become distinctly coarser with an average grain size of 0.24 mm in diameter. The grain size of muscovite varies between 0.015 and greater than 0.75 mm in diameter. The well-developed needles of muscovite sometimes occur like encarrioblasts. Porphyroblasts of chlorite are common. The original texture of the country rock was never disturbed in the early phase of alteration and recrystallisation. Textural obliteration is more conspicuous in the later stage of

alteration or sometimes adjacent to the ore bodies.

Permeability and porosity

Permeability of a host rock is an important factor that controls epigenetic mineralisation. The wall-rocks have generally become more or incompetent due to the effects of alteration.

The earlier phase of dolomitization was mainly responsible for a slight increase in porosity without any increase in the volume.

B. Mineralogical changes due to alteration

Significant mineralogical changes have been recorded from the rocks surrounding the ore zones. Chlorite and biotite occur persistently in the ore zone as well as outside although their proportions vary. These minerals also show a progressive change and variations in their quantities towards the ore bodies which is a significant feature and most characteristic of the hydrothermal deposits (Lindgren, 1913; Schwartz, 1959 and Parks Jr. and MacDiarmid, 1964). Schwartz (1959) compiled a list of 65 minerals formed by hydrothermal alteration and considered biotite, chlorite, sericite and quartz as the important hydrothermal minerals. The minerals constituting the country rocks in the area under investigation, show a variety of alteration products. The chemical changes show that there exists a relationship between the composition of the primary mineral and the related alteration products. Biotite in these rocks was commonly altered first.

Spurer (1898) was the first person who introduced a variety of fine-grained chalcedonic quartz as jasperoid and Irving (1904,1911)was

one of those early workers to describe jasperoid silicification in the Black Hills, S.Dakota, U.S.A. Silica played an important role during the hydrothermal alteration and the silicification, like biotitization, chloritization and sericitization, was also intense. Hydrothermally altered rocks in the work area were later silicified by jasperoid.

The general nature and sequence of wall-rock alteration is as follows :

1. Dolomitization
2. Silicification
3. Biotitization
4. Chloritisation and
5. Sericitisation

Biotite, which is supposed to be one of the important minerals in hydrothermally altered rocks, shows the incipient stages of alteration into green to light brown biotite and chlorite. According to Schwartz (1958), the alteration of biotite by hydrothermal solutions at moderate temperature and pressures is very much effective.

In the course of recrystallisation, biotite formed an aggregate of ligher brown coloured crystals. The alteration of biotite seems to be closely related to the associated clusters of rutile needles (Deer, et al., 1961). The concentration of rutile grains in the altered zones was found to be an indication of the zone of biotite alteration. The progressive alteration further affected the chlorite

and resulted in the formation of sericite, another characteristic alteration product. However, such alteration of biotite or chlorite is generally partial. The equilibrium is rarely reached in the hydrothermal alteration of biotites. Schwartz (1959) pointed out that "recrystallised biotite is always earliest when present, and that this is commonly followed by chlorite". The chlorite is an important mineral of the hydrothermal sequence of the wall-rocks of the area. Where the alteration is more advanced, chlorite becomes an important hydrothermal mineral and is found associated with talc (Park Jr. and MacDiarmid, 1964). This is very evident in Peku and Rangpo mine areas, where chlorite talc assemblage is conspicuous. Chlorite is therefore a diagnostic hydrothermal mineral of these deposits. Deer et al. (1961) believed that many low temperature hydrothermal veins of Alpine type in low grade metamorphosed sediments carry chlorite in addition to quartz, etc.

According to the foregoing discussions, chlorite, sericite, biotite, talc and quartz are the common minerals in the ore zones although their relative proportions vary.

A comparative study of biotite and chlorite in the rocks occuring around mineralized and non-mineralized zones was also made in order to record their quantitative and qualitative variations that may have some bearing on rock alteration.

Chlorite and biotite content

It is very clear from the variation diagram (Fig.28) that the chlorite and biotite content increases towards the ore zone suggesting

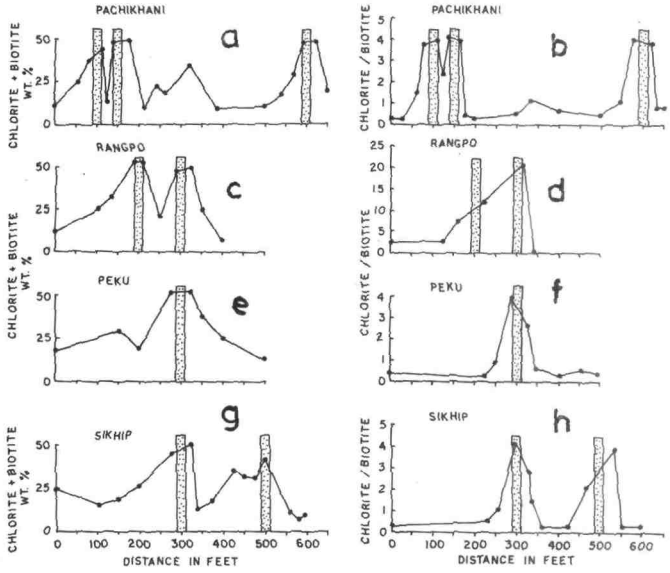


FIG. VARIATION DIAGRAM SHOWING CHANGES IN THE CHLORITE AND BIOTITE CONTENT IN THE WALLROCKS AT VARIOUS COPPER DEPOSITS AROUND DARJEELING HIMALAYAS

Fig. 28

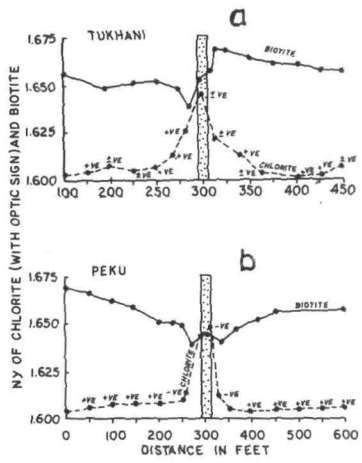


FIG. VARIATION DIAGRAM SHOWING CHANGES IN REFRACTIVE INDEX (Ny) OF CHLORITE (WITH OPTIC SIGN) AND BIOTITE, IN THE WALLROCKS AT PEKU AND TUKHANI COPPER DEPOSITS AROUND DARJEELING HIMALAYAS

Fig. 29

their leaching of iron contents towards the lode. The value of index of refraction of biotite varies from a minimum of 1.638 in the ore zone to a maximum of 1.670 in the non-mineralised rocks (Fig. 29). The changes in the optical properties of chlorite are also very diagnostic and characteristic. The intermediate index of refraction (Ny) of chlorites is found to be of the order of a minimum of 1.601 in the non-mineralised rocks and a maximum of 1.648 in the mineralized zones (Fig. 29). There is also a well marked change in their optic sign to negative nearer to the lode (Fig. 29). This indicates a decrease in Al and an increase in Fe of these chlorites towards the lode. This is also clearly evident from the results of chemical analysis of chlorites from the altered/mineralised and unaltered/non-mineralized zones (Fig. 34a). Conspicuously, the percentage of chlorite and biotite record high values in the ore zones (Fig. 28). On the contrary, generally in the non-mineralized zone, they record lower values except in two cases (Fig. 28a, and e), which may be due to local abnormalities. It is, therefore, evident that chlorite and biotite are preferentially concentrated in mineralized zones as a result of later hydrothermal activity. The chlorite/biotite ratio also significantly varies from a minimum of 0.25 in the non-mineralized zones to a maximum of 21 in the mineralised zones (Fig. 28).

Refractive index (Ny) of biotite and chlorite (with optic sign)

The variation diagram (Fig. 29) shows that the values of intermediate index of refraction (NY) of biotite steadily decrease. But sometimes reversed relations are also present and show the presence of two different compositional varieties of chlorite. Under such circumstances, the compositional variation of the coexisting biotites shows a remarkable regular pattern. No doubt, the variation of their optical sign is found to be always regular (Fig. 29), but there is a characteristic and well marked change in their pleochroic scheme. The replacement of biotite to chlorites along the basal cleavage is a regular feature. In most of the cases there is a well marked sequence of this replacement, starting from the normal brown biotite to faded brown and thence to a green biotite, which in turn alters to green chlorite. The presence of secondary biotite formed during the hydrothermal activity is very common. Sometimes its accumulation in the wall-rocks is very high and the rocks become biotitic as found at Kalimpong and Rangpo mines. A well-marked and noteworthy feature observed in this replacement is the absence of iron ore inclusions within the replacing chlorites. Schwartz (1959) stated, "During the replacement of biotite to chlorite, equillibrium is usually not achieved, and the original composition of biotite plays a strong influence on the composition of the replacing chlorite". This partly explains the observed irregularity in the compositional variation of these chlorites as indicated by the anomalous variation of their optical characters in the zone of wall-rock alteration (Fig. 29).

Pleochroism of biotite

In the country rocks or in the non-mineralised zones the biotites show usual and normal pleochric schemes. For example, in the non-mineralized schists, near Rangpo mines, the pleochroic scheme was found to be normal as X = light yellow, Y = brown, and Z = deep brown with absorption - $Z > Y > X$. But in the mineralised parts of the schists which are highly chloritic and biotitic near Rangpo mines, an unusual colour and abnormal pleochroic scheme as X = almost colourless, Y = green and Z = deep greenish black was noted. The absorption being $X < Y < Z$. Similar variations in the pleochroic scheme of biotites have been invariably noted in the non-mineralised and mineralised rocks from other parts of the area. The biotite from the mineralised zone at Kalimpong recorded an abnormal pleochroic scheme as X = pale brownish yellow, Y = brown and Z = very deep brown, where the absorption is $X < Y \leq Z$. These marked variations in the pleochroic scheme of biotite indicate the well-marked zones of wall-rock alteration, where the biotite has been affected chemically as well as physically.

C. Chemical changes due to alteration

An attempt has been made to investigate the complex chemical changes suffered by the various wall-rocks of the hydrothermal copper ore deposits of Darjeeling Himalayas. Chemical analysis of carefully selected samples from the altered and unaltered country rocks and minerals of the various deposits permitted a general assessment of the results.

Chemical characteristics of wall-rocks

Generally, the wall-rocks have been so much affected and altered by the invading hydrotherms that often it is a problem to determine the nature of chemical change. However, proper care has been taken to interpret the analytical results (Tables 37 to 40) of the samples which are presented in the form of variation diagrams (Figs. 30,31,32 & 33).

It is revealed that the chemical changes are complex, while some of the elements are added to rocks by the action of hydrothermal solutions, still there are others which are removed from the rocks (Figs. 30, 31, 32 and 33).

Prominent chemical changes also occurred due to addition of some compounds and to removal of some others. Silica, magnesia, potassium, carbon dioxide, iron, sulphur and water are the important additions and lime, soda, alumina and phosphorous pentoxide are those which are removed from the system.

Mineralisation of copper is restricted mainly to four kinds of country rocks in the area, viz., slates, phyllites, schists and

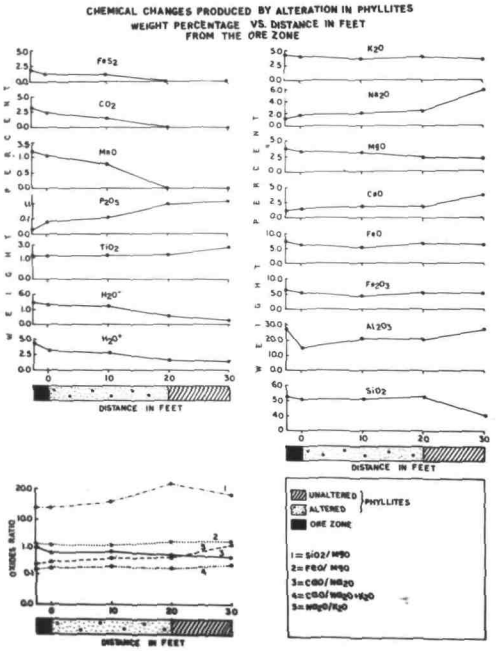


Fig. 30

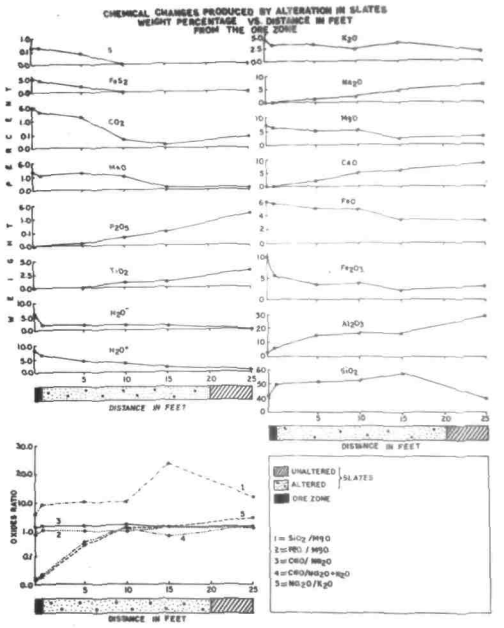


Fig. 31

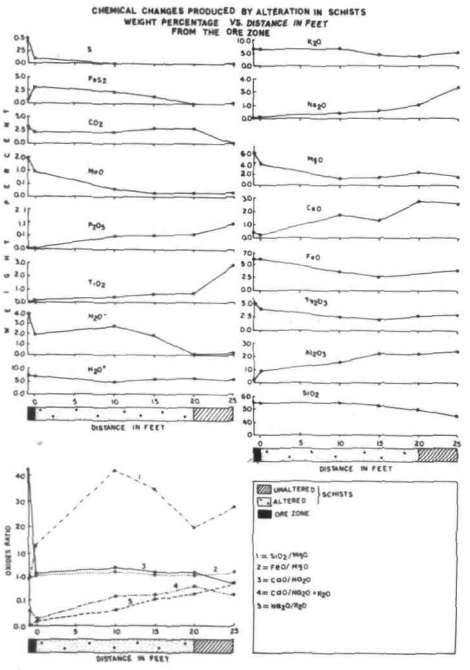


Fig. 32

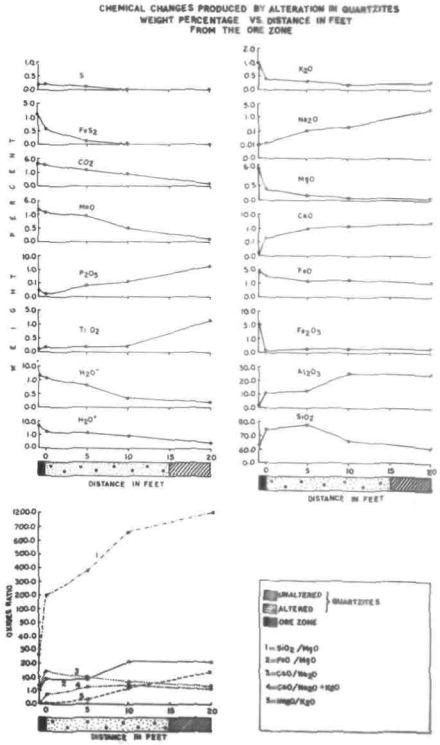


Fig. 33

quartzites. Not only the altered but also the unaltered rocks are taken into consideration for this study.

Silica

The SiO_2 contents in the unaltered phyllites, schists, slates and quartzites (Tables 30, 32, 34 & 36) are found to be 40.20, 44.72, 38.60 and 60.80 per cent respectively. The SiO_2 content increases gradually from the altered rocks to the copper ore zones where the same rocks recorded 52.35, 56.00, 41.00 and 62.35 per cent respectively. It is, therefore, evident that the schists are much more silicified than the slates and quartzites in the highly altered ore zone.

Alumina and titania

Alumina and titania show a general decrease in their contents from unaltered to altered zones. Al_2O_3 contents in the unaltered phyllites, schists, slates and quartzites are found to be 26.20, 24.40, 28.65 and 24.60 per cent respectively. There is a marked depletion of Al_2O_3 in the schists, slates and quartzites from the altered rocks to the ore zone where the values of alumina with respect to the rocks concerned are 2.10, 2.00 and 1.01 per cent. In the phyllites, however, alumina indicates a different concentration trend altogether. Alumina has a tendency to decrease in the altered phyllites adjacent to ore zones (15.45 per cent) and to increase sharply in the ore zone itself (27.12 per cent). The general decrease in alumina from unaltered to altered zones is found to vary from 11 to 25 per cent. All the four rock types show a general decrease in TiO_2 contents from the unaltered through altered to ore zone. About 50 per cent of TiO_2 in the unaltered

zone was depleted in the altered ore-zone.

Ferric oxide and ferrous oxide

All the four types of unaltered rocks are comparatively poor in iron oxides than the corresponding altered rocks. The ferrous oxide exceeds ferric oxide in all the unaltered rocks. However, the same FeO-Fe_2O_3 relationship is not always maintained in altered rocks near the ore zones. For example, in the altered slates ferrous oxide slightly exceeds ferric oxide (Fe_2O_3, 5.60; FeO, 5.80) and this ratio continues upto near the ore zones. But a reversal in their relative proportion is indicated in the ore zone proper where ferric oxide (10.00 per cent) exceeds ferrous oxide (6.00 per cent). A progressive increase in both the oxides of iron in all the types of rocks the unaltered through altered to ore zones, has been recorded. In general, the ferric and ferrous oxides increase in the altered zones.

Lime and magnesia

Lime and magnesia show different trends in the altered wall-rocks as well as in ore zones. Lime content records a progressive decrease from the unaltered zones through altered to ore zones where it has minimum content. But unlike CaO, MgO shows a progressive increase from the unaltered through altered rocks to the ore zones.

Potash and soda

These two constituents have opposite relation with respect to their contents in the wall-rocks as well as in the ore zones. While the potash content shows a sharp increase, the soda content shows a

sharp decrease in all the rocks collected from the unaltered through altered to ore zones.

Water

The total water ($H_2O \pm$) content of the unaltered rocks is much lower than that of the altered rocks. The water content records a sharp increase towards the ore zone. The maximum amount of water is concentrated in and around the ore zones which are supposed to be the centres of intense hydrothermal activity. All the rock types, viz., phyllites, schists, slates and quartzites, indicate a significant rise in total water content from the unaltered through altered to the ore zone.

Manganese and carbon dioxide

Like water, manganese and carbon dioxide are typically associated with altered wall-rocks. In the unaltered phyllites both MnO and CO_2 are practically absent. But the phyllites in the altered zone, about 10 ft. away from the ore zone, have 0.78 and 1.32 per cent of MnO and CO_2 respectively. In the ore zone the amount of MnO and CO_2 in the phyllites reached upto 2.01 and 3.20 per cent respectively. Other unaltered rock types, viz., the schists, slates and quartzites, however, recorded 0.03, 0.10 and 0.10 per cent of MnO, and 0.01, 0.08 and 0.20 percent of CO_2 respectively. Therefore, in phyllites, the proportions of MnO and CO_2 progressively increase from the unaltered through the altered to the ore zones.

Ferrous sulphide and sulphur

Ferrous sulphide and sulphur are found to be important constituents of the altered rocks as well as of the ore zone. The unaltered rocks are almost free from these two constituents. They do not, however, have any regularity in their concentration trends in the different rocks. Phyllites belonging to the altered and ore zones have more or less the same value of FeS_2.

Phosphorous pentoxide

The P_2O_5 content shows a sharp decline from the unaltered through altered rocks to the ore zone, recording a minimum value of the constituent. The P_2O_5 contents in the unaltered phyllites, schists, slates and quartzites are 2.08, 1.13, 2.92 and 2.15 per cent respectively, whereas the corresponding rocks in the ore zone have negligible amounts of P_2O_5. The P_2O_5 content is, therefore, mainly limited to the unaltered zones.

Oxide ratios

The oxide ratios of some major constituents of the rocks in all the three zones have been calculated and plotted in the variation diagrams (Figs. 30, 31, 32 and 33). SiO_2/MgO, FeO/MgO, $CaO/(Na_2O + K_2O)$ and Na_2O/K_2O ratios from the unaltered through altered rocks to the ore zone have been plotted.

From the pattern of the distribution of various major elements already described, it is, therefore, revealed that the wall-rocks have suffered changes in chemical composition during this process leading to the ore deposition.

Chemical alteration of the wall-rocks prior to ore deposition

Adequate lithological and petrological evidence is available to conclude that the alteration of the wall-rocks prior to deposition of copper ore, started with dolomitisation and ended with sericitisation, the sequence of alteration being dolomitization-silicification-biotitisation-chloritisation-sericitisation.

It may be noted that the primary biotite, which was already present in the rock as an important constituent, underwent reconstitution.

The further action of hydrotherms resulted in the formation of chlorite and uniaxial muscovite. The variation of chlorite/biotite ratio in the ore zone is a function of both the H^+ ion concentration in the hydrotherms and the biotite content in the earlier rocks.

Chemical characteristics of chlorite and biotite in the phyllites of unaltered and altered zones

The variations in the chemical composition of biotite and chlorite derived from the phyllites of the ore-zones and the barren country rocks have been plotted (Fig. 34 (a,b), Tables 41 and 42). They are also later compared with the biotites derived from the granitic rocks of the area under investigation.

Chlorites (Fig. 34a)

The limited chemical study that was made on chlorites occurring as mineral constituents of phyllites, suggests that their composition in the altered and copper ore zones is different from that in the unaltered zones. Thus the difference in composition of chlorites within and away

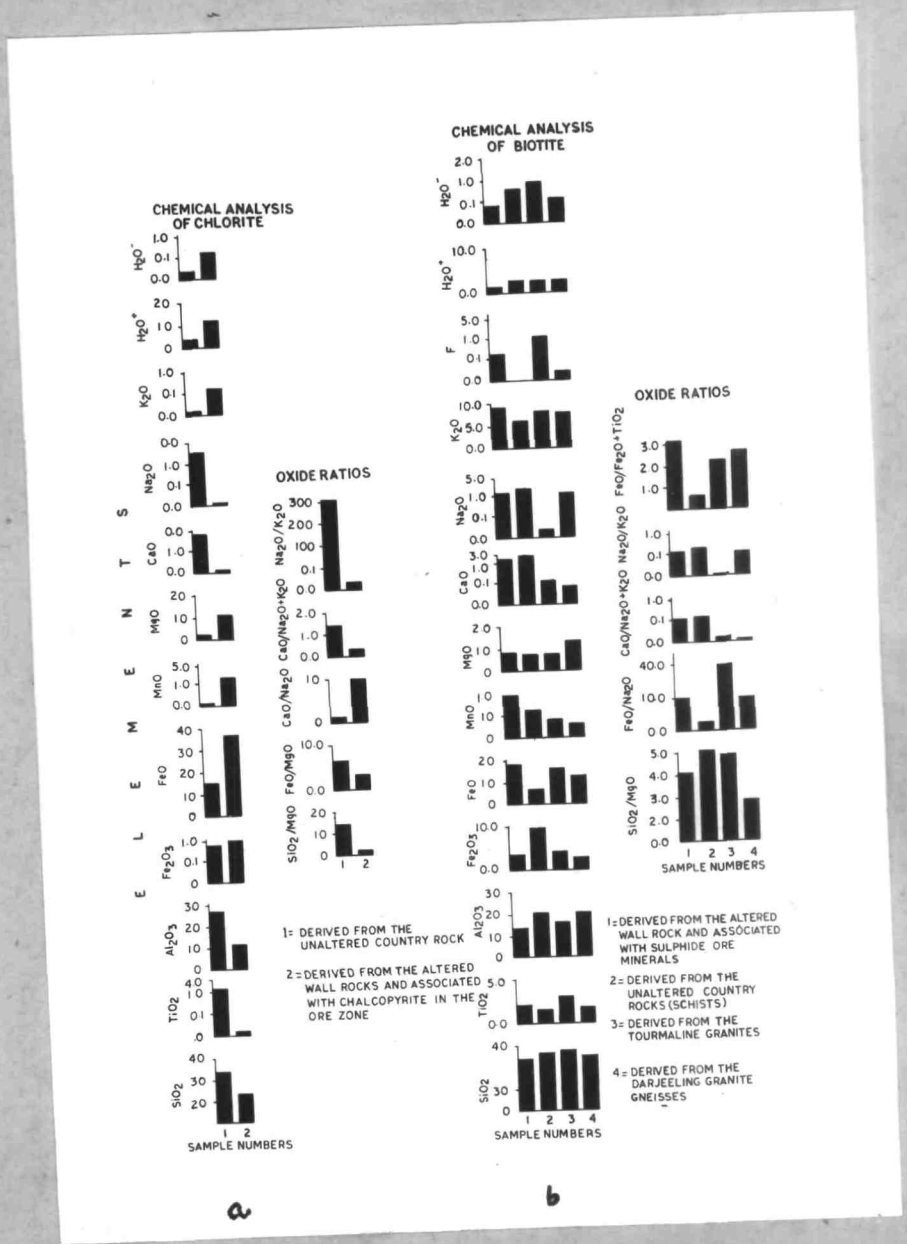

CHEMICAL ANALYSIS OF CHLORITE
ELEMENTS
H2O-
H2O+
K2O
Na2O
CaO
MgO
MnO
FeO
Fe2O3
Al2O3
TiO2
SiO2
SAMPLE NUMBERS
OXIDE RATIOS
Na2O/K2O
CaO/Na2O+K2O
CaO/Na2O
FeO/MgO
SiO2/MgO
1= DERIVED FROM THE UNALTERED COUNTRY ROCK
2= DERIVED FROM THE ALTERED WALL ROCKS AND ASSOCIATED WITH CHALCOPYRITE IN THE ORE ZONE
a
CHEMICAL ANALYSIS OF BIOTITE
H2O-
H2O+
F
K2O
Na2O
CaO
MgO
MnO
FeO
Fe2O3
Al2O3
TiO2
SiO2
SAMPLE NUMBERS
OXIDE RATIOS
FeO/Fe2O+TiO2
Na2O/K2O
CaO/Na2O+K2O
FeO/MgO
SiO2/MgO
1=DERIVED FROM THE ALTERED WALL ROCK AND ASSOCIATED WITH SULPHIDE ORE MINERALS
2= DERIVED FROM THE UNALTERED COUNTRY ROCKS (SCHISTS)
3= DERIVED FROM THE TOURMALINE GRANITES
4= DERIVED FROM THE DARJEELING GRANITE GNEISSES
b

Fig. 34

from the ore zone is obviously due to the effect of hydrothermal solutions. This has enriched chlorites in some chemical compounds and impoverished in some others. The results of chemical analyses of chlorites (Table 41), plotted in the form of variation diagrams, are self-explanatory.

Silica

The SiO_2 content in the chlorites derived from the phyllites in unaltered zones around the Sikhip copper deposits is considerably higher than that occurring in the chlorites, derived from the same rocks in the altered as well as in the ore zones.

Alumina and titania

The Al_2O_3 and TiO_2 contents in the altered zone close to the ore deposit record higher values than those in the unaltered zones.

Ferric oxide and ferrous oxide

The amounts of ferric oxide in the unaltered and altered rocks do not indicate much variation. But the chlorites in the altered rocks contain ferrous oxide more than double of its amount present in unaltered rocks.

Lime and magnesia

Chlorites in the altered zones are considerably enriched in MgO and impoverished in CaO in comparison to the unaltered zones.

Potash and soda

Potash records a slight increase and soda a marked decrease in the altered zone.

Manganese

Chlorites in the altered zone record a marked rise in its MnO content as compared to those in the unaltered zone.

Water

The chlorites of the altered zone have a total water content, about three times more than that occurring in the chlorites of the unaltered zone.

Oxide ratios

All the oxide ratios, except CaO/Na_2O, viz., SiO_2/MgO, FeO/MgO, $CaO/Na_2O + K_2O$ are considerably higher in the chlorites of unaltered rocks than those in the chlorites of altered zone. CaO/Na_2O ratio, however, increases in the altered zone.

The variations in the major chemical constituents and their oxide ratios in the chlorites, separated from the unaltered and altered country rocks of Sikhip copper deposits, are so conspicuous that they can happen only when there is a profound change in the chemical environment leading to rock alteration but to a limited extent.

Biotite

The analytical results of the biotites derived from the phyllites in the unaltered as well as in altered parts of the country rocks adjacent to Peku copper deposit have been studied. The tables as well as the corresponding histograms (Fig. 34 b) of the chemical compositions of biotites indicate that their compositions have been largely influenced by their geological environments.

The major chemical constituents in the biotites from the altered and mineralized wall-rocks and in those from unaltered rocks have some regularity in their distribution trends.

The biotites derived in the mineralized zone show an increase in the proportions of FeO, MgO and K_2O contents and a decrease in Al_2O_3, Fe_2O_3 and Na_2O contents (Table 42). As far as TiO_2, MnO, SiO_2 and CaO are concerned, the difference in their percentage compositions are rather insignificant. The biotites derived from the unaltered rocks show a complete absence of fluorine which is characteristically present in the biotites found in the altered rocks. The variations in oxide ratios are also very significant, e.g., SiO_2/MgO, $CaO/Na_2O + K_2O$ are found to be slightly lower, and FeO/Na_2O, and $FeO/Fe_2O_3 + TiO_2$, are appreciably higher in the biotites associated with the mineralised wall-rocks, than in those occurring in the unaltered rocks. A comparative chemical study of biotites derived from the younger granites and those from the altered wall-rocks shows that some of these oxides have similar trend of distribution (Table 42).

III. Isotope variation in the country rocks and ore deposits

Isotopic studies dealing with the natural variations of the abundances of certain elements are of current interest and importance in geology, geochemistry and geochronology. An attempt has been made to solve certain problems pertaining to the mineralization and age of the base metal deposits of the area. Isotopic values of natural non-radiogenic oxygen, carbon and sulphur and also of radiogenic lead isotopes were determined.

A. Distribution of δO^{18} and δC^{13} values

1) Lead-zinc deposit

Engel and others (1958) made a detailed study of the oxygen and carbon isotopes of a hydrothermal alteration zone around the lead-zinc-silver ore bodies at Leadville and Gilman, Colorado. More recently, Pinckney and Rye (1972) have studied the variation of O^{18}/O^{16}, C^{13}/C^{12} ratios in altered limestones in Hill Mine, Cave-in district, Illinois. It may be regarded as the first attempt to study the variation in the isotopic composition of the ore-bearing rocks in the Eastern Himalayas.

The highest values in the unaltered rocks are 26.5% δO^{18} (SMOW) and 2.5% δC^{13} (PDW) (Table 22, Fig. 35a). The isotopic values in the altered rocks are found to be as low as 8.0% δO^{18} (SMOW) and -4.0% δC^{13}. It is also of interest to note here that the low values of δO^{18} and δC^{13} are dependent on the grain size (Table 20).

TABLE - 20 Isotopic analysis of two samples showing marked textural difference

δO^{18}‰	δC^{13}‰	Average size of minerals		Rock type
		Calcite	Dolomite	
8.5	- 3.0	0.004	1.5	Dolomitic limestones (altered)
26.5	2.5	1.5	0.5	Limestone(unaltered)

The grain-size relation between calcite and dolomite has been adequately stated earlier while discussing the petrographic characters of the limestones. The lithological and other physical changes were

brought about in the limestones as alteration became more pronounced with the intensity of dolomitisation leading to the reduction in the size of calcite grains and their partial replacement by dolomite. The δO^{18} and δC^{13} values show a tendency to decrease at the contact of the unaltered and altered limestones and finally they record lowest values near the ore zones (Table 22 , Fig.35a,b). In the unaltered limestone the range of oxygen and carbon isotopes is similar to/most that in of the marine limestones throughout the world (Taylor, 1967).

It is obvious that because the limestones in the altered zones were recrystallised, dolomitized and continued to remain sufficiently porous to allow fluids to pass through them, their isotopic values became quite different from those rocks which remained unaffected during alteration. δO^{18} variations in the altered rocks, therefore, reflect a thermal gradient.

The variation of δC^{13} values in the altered dolomitic limestones indicate that a large amount of carbon was involved during alteration. According to Pinckney and Rye (1972), "The amount of carbon required for the amount of exchange means that a large volume of water passed through the rocks during recrystallisation. A large volume of water is consistent also with the amount of water required for the transportation of silica deposited in the wall rock, and the amount required by partial exchange of oxygen isotopes".

Therefore, a large volume of water is required for the introduction of quartz and with the amount of carbon needed to change δC^{13} values of the rock. The main source of such a large amount of water

could be the hydrotherms. According to Pinckney and Rye (1972), "... for a simple system in which carbon-bearing aqueous fluid passes through a porous limestone and continuously exchanges isotopes of carbon and oxygen at equilibrium along its course, the isotopic ratios of O^{18}/O^{16} and C^{13}/C^{12} in both the fluid and the rock should vary systematically".

The δO^{18} values of calcite, quartz and dolomite crystals and δC^{13} values of calcite from altered and unaltered zones have also been plotted in the variation diagrams. All of these variation diagrams show a systematic decrease in isotopic values of δO^{18} and δC^{13} from the unaltered rocks towards the ore-zone (Fig. 35c,d).

TABLE - 21 Isotopic composition of quartz, calcite and dolomite in the carbonate rocks, Rishi area.

Serial No.	Mineral	Altered dolomitic limestones		Unaltered limestones	
		δO^{18} (SMOW)	δC^{13} (PDB)	δO^{18} (SMOW)	δC^{13} (PDB)
1	Quartz	+ 15.3	-	+ 23.0	-
2	Quartz	+ 8.0	-	+ 20.5	-
3	Quartz	+ 16.5	-	+ 20.0	-
4	Quartz	+ 17.3	-	+ 18.5	-
5	Quartz	+ 10.0	-	+ 18.0	-
6	Calcite	+ 22.5	- 0.10	+ 25.1	+ 0.88
7	Calcite	+ 16.9	- 0.20	+ 24.8	+ 0.88
8	Calcite	+ 13.8	- 0.20	+ 23.5	+ 0.88
9	Calcite	+ 11.0	- 0.64	+ 23.0	+ 0.65
10	Calcite	+ 8.9	- 0.80	+ 22.5	+ 0.40
11	Dolomite	+ 9.6	-	+ 24.5	-
12	Dolomite	+ 10.0	-	+ 24.5	-
13	Dolomite	+ 12.0	-	+ 24.5	-
14	Dolomite	+ 13.0	-	-	-
15	Dolomite	+ 16.0	-	-	-

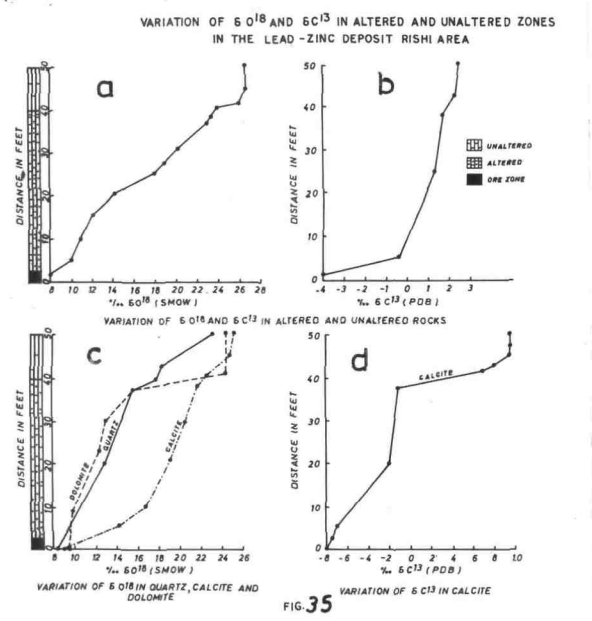


Fig. 35

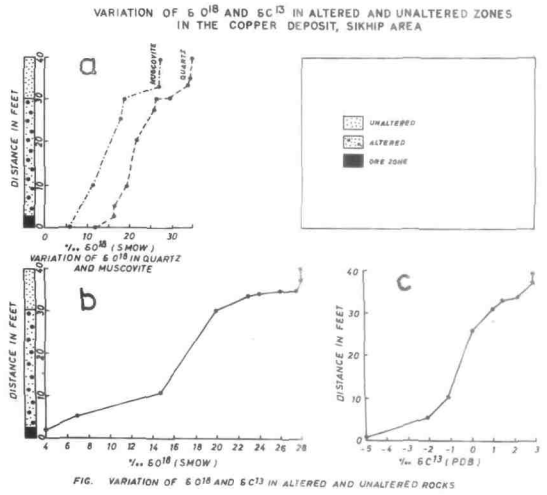


Fig. 36

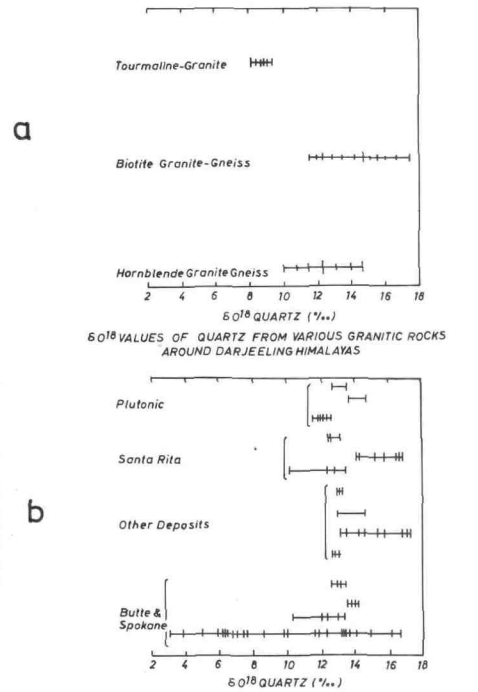


Fig. 37

TABLE - 22 δO^{18} and δC^{13} values in the altered and unaltered carbonate rocks, Rishi area.

Serial No.	Altered dolomitic limestones		Unaltered limestones	
	δO^{18} (SMOW)	δC^{13} (PDB)	δO^{18} (SMOW)	δC^{13} (PDB)
1	+ 23.0	+ 1.6	+ 26.5	+ 2.5
2	+ 20.0	+ 1.5	+ 25.5	+ 2.4
3	+ 18.0	+ 1.3	+ 25.5	+ 2.3
4	+ 14.0	+ 0.9	+ 26.5	+ 2.3
5	+ 12.0	+ 0.5	+ 26.2	+ 2.2
6	+ 11.0	0.0	+ 26.0	+ 2.1
7	+ 10.0	- 1.6	+ 24.0	+ 1.0
8	+ 8.5	- 3.0	-	-
9	+ 8.0	- 4.0	-	-

2) Copper deposits

According to the earlier statement, the phyllites around the copper deposits of Sikhip developed distinct zones of silicification, biotitization, chloritization and sericitisation. An attempt has been made to study the oxygen and carbon exchange between the altered rocks and invading hydrotherms by collecting the relevant data on the oxygen and carbon isotopic variations from the unaltered parent rocks upto the altered rocks in the ore zones. Also, the isotopic values δO^{18} of quartz and muscovite belonging to altered and unaltered rocks have been plotted (Figs. 36a,b,c; Tables 23 & 24).

The δO^{18} and δC^{13} values of altered rocks progressively decrease towards the ore body (Figs.36a,b; Table 23). For example, in the unaltered rocks, δO^{18} and δC^{13} values range from 20 to 28 (SMOW), and 1 to 3 (PDB) respectively. Whereas in the altered rocks, δO^{18}

TABLE -23 Variations of δO^{18} and δC^{13} values in altered and unaltered rocks, Sikhip area.

ALTERED ROCKS (Phyllites)		UNALTERED ROCKS (Phyllites)	
δO^{18} (SMOW)	δC^{13} (PDB)	δO^{18} (SMOW)	δC^{13} (PDB)
+ 19.4	+ 0.5	+ 28.0	+ 3.0
+ 18.3	0.0	+ 28.0	+ 3.0
+ 17.2	- 1.7	+ 27.8	+ 2.5
+ 16.0	- 1.4	+ 22.0	+ 1.5
+ 14.0	- 1.0	+ 20.0	+ 1.0
+ 10.5	- 2.5	-	-
+ 7.0	- 2.0	-	-
+ 5.0	- 4.0	-	-
+ 4.0	- 5.0	-	-

TABLE -24 δO^{18} variation in quartz and muscovite collected from the altered and unaltered zones, Sikhip area

No.	Name of mineral	ALTERED ROCKS (Phyllites) δO^{18} (SMOW)	UNALTERED ROCKS (Phyllites) δO^{18} (SMOW)
1	Quartz	+ 14.0	+ 17.8
2	Quartz	+ 13.0	+ 17.8
3	Quartz	+ 12.5	+ 17.5
4	Quartz	+ 11.8	+ 17.0
5	Quartz	+ 10.5	+ 15.8
6	Quartz	+ 10.4	+ 14.5
7	Quartz	+ 10.0	-
8	Quartz	+ 8.9	-
1	Muscovite	+ 11.2	+ 14.8
2	Muscovite	+ 11.0	+ 14.8
3	Muscovite	+ 10.2	+ 14.0
4	Muscovite	+ 9.3	+ 13.0
5	Muscovite	+ 9.0	+ 12.0
6	Muscovite	+ 8.5	+ 11.4
7	Muscovite	+ 7.5	-
8	Muscovite	+ 6.3	-

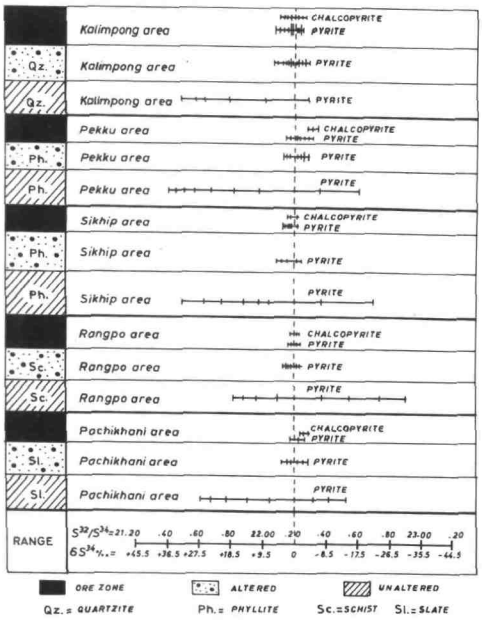


FIG. S^{32}/S^{34} RATIOS AND PERMIL VALUES OF SULPHIDE MINERALS FROM COPPER DEPOSITS AROUND DARJEELING HIMALAYAS

Fig. 38

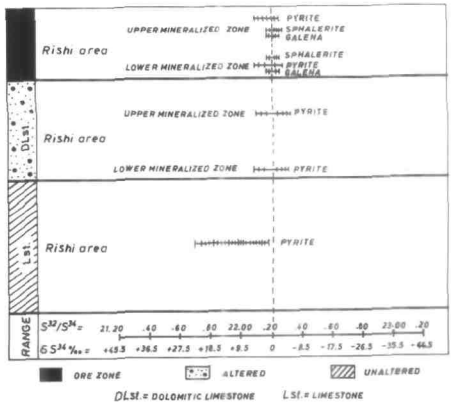


FIG. S^{32}/S^{34} RATIOS AND PERMIL VALUES OF SULPHIDE MINERALS FROM LEAD-ZINC DEPOSITS AROUND DARJEELING HIMALAYAS

Fig. 39

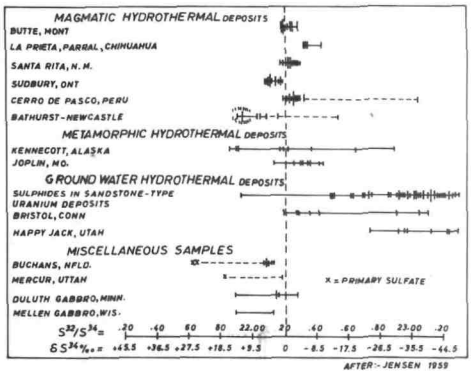


FIG. S^{32}/S^{34} RATIOS AND PERMIL DEVIATIONS OF VARIOUS SULFIDE MINERALS FROM DIFFERENT MINERAL DEPOSITS

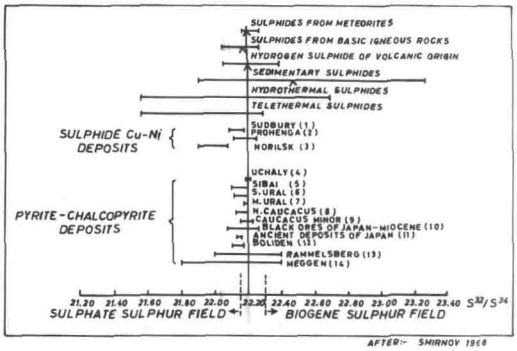


FIG. THE VARIATIONS OF SULPHUR ISOTOPE COMPOSITION IN SULPHIDES

Fig. 40

isotope in quartz and muscovite decreases from 14.5 to 8.9 (SMOW) and from 14.8 to 6.4 (SMOW) respectively, as the ore zone is approached. The same isotopes in the quartz and muscovite of unaltered rocks vary from 15.0 to 17.9 (SMOW) and from 11.8 to 14.8 (SMOW) respectively. It is, therefore, evident that the isotope ratios are higher in the unaltered rocks in comparison to the altered ones.

B. Distribution of S^{32}/S^{34}

Ore samples for this study were selected from the various Cu and Pb-Zn deposits falling within the area. They were analysed to determine the isotopic composition of sulphur and the results are presented in Table 25. The values are plotted as S^{32}/S^{34}, and as δS^{34} relative to standard Canyon Diablo Troilite (Figs. 38 and 39). The results are compared with the standard S^{32}/S^{34} ratios and permil deviations of various other sulphide minerals of the world compiled by Jensen (1959) after the work of Kulp et al. (1956), Jensen (1957), and Jensen and Amstutz (1959). Smirnov (1968) also summarized the results of the variations of sulphur isotope composition in sulphides (Fig. 40a, b) determined by Russian geologists.

The S^{32}/S^{34} ratios in the lead-zince deposits of Rishi area show that they have more or less a common variation range in the altered as also in the ore zone. For example, the sulphur ratios of pyrite, sphalerite and galena vary from 22.10 to 22.25 in the altered rocks and 22.18 to 22.25 in the ore zone. Somewhat similar rangesof isotopes in the pyrite in the altered rocks (dolomitic limestones) adjacent to ore-zone have been found (Fig. 39). The isotopic range in the pyrites in unaltered rocks is different and the S^{32}/S^{34} ratios vary from

TABLE - 25 Description and S^{32}/S^{34} ratios of some sulphide minerals

No.	Description and location of sulphide minerals	S^{32}/S^{34}	‰ S^{34}
1	Chalcopyrite occurs with pyrite, phyllite wall-rock; Sikhip area	+ 22.18	+ 1.9
2	Chalcopyrite occurs with pyrrhotite, phyllite wall-rock; Pekku area	+ 22.30	- 4.2
3	Sphalerite dark brown, dolomitic limestone wall-rock; Rishi area	+ 22.28	- 3.7
4	Chalcopyrite occurs with pyrite quartzite wall-rock; Kalimpong area	+ 22.27	- 3.6
5	Pyrite occurs with sphalerite and galena, dolomitic limestone wall-rock; Rishi area	+ 22.27	- 3.6
6	Pyrite occurs with chalcopyrite, phyllite wall-rock; Sikhip area	+ 22.23	- 2.4
7	Pyrite occurs with sphalerite, dolomitic limestone wall-rock; Rishi area	+ 22.21	- 0.5
8	Pyrite fine-grained, dolomitic limestone wall-rock; Rishi area	+ 22.29	- 4.0
9	Pyrite coarse grained, occurs with chalcopyrite and pyrrhotite, schist wall-rock; Rangpo area	+ 22.36	- 7.5
10	Pyrite fine grained variety, associated with chalcopyrite and pyrrhotite, slate wall-rock; Pachikahni area	+ 22.20	0.0
11	Pyrite associated with pyrrhotite and chalcopyrite; slate wall-rock; Pachikhani area	+ 22.22	- 1.9
12	Galena coarse grained crystal, dolomitic limestone wall-rock; Rishi area	+ 22.28	- 3.2

(Contd.)

Table 25 (continued)

13	Galena coarse grained crystal, dolomitic limestone wall-rock; Rishi area	+ 22.28	- 3.2
14	Chalcopyrite associated with pyrite; phyllite wall-rock; Sikhip area	+ 22.30	- 4.2
15	Pyrite taken from schists (unaltered country rocks); Rangpo area	+ 21.80	+ 18.5
16	Pyrite taken from phyllites (unaltered country rocks), Sikhip area	+ 21.60	+ 27.5
17	Pyrite taken from phyllites (unaltered country rocks); Pekω area	+ 21.40	+ 36.5
18	Pyrite taken from slates (unaltered country rocks); Pachikhani area	+ 21.60	+ 27.5
19	Pyrite taken from limestones (unaltered country rocks); Rishi area	+ 21.70	+ 23.00
20	Pyrite taken from limestones (unaltered country rocks); Rishi area	+ 22.00	+ 9.5

21.68 to 22.19. This range is wide and it bears no relation with that found in the altered rocks adjacent to ore zone, or in the ore-zone proper. Therefore, pyrite, sphalerite and galena in the ore-zone and the pyrite in the altered rocks adjacent to ore-zone may be genetically correlated. But the range of sulphur isotope in the pyrite found in the unaltered limestones indicates that it is definitely of a sedimentary origin.

The variations of S^{32}/S^{34} ratios in some of the copper deposits have been shown in Fig. 38 . In the ore zones chalcopyrite and pyrite were analysed while in the adjacent altered wall rocks and the unaltered country rocks, pyrite was analysed. The S^{32}/S^{34} ratios in the ore zones and the adjacent altered country rocks show a narrow range in comparison to the wide variation S^{32}/S^{34} ratio in the unaltered country rocks. Sulphur isotope ratios of chalcopyrite in the ore zone at Rangpo and Sikhip mines and the altered wall rocks show a range of 22.18 to 22.22. At Pachikhani, Peku and Kalimpong they have ranges of 22.22 to 22.25, 22.25 to 22.35 and 22.10 to 22.25 respectively. The variations in sulphur isotope ratios in these deposits are very narrow.

Probable source and nature of mineralisation

The question of the source of the base metal deposits occurring not only in this part of the Himalayas but also elsewhere in western Himalayas has been an enigma for a long time. It is, therefore, intended to throw some valuable light on their probable source. As stated earlier that there are two different suites of granitic rocks in the study area,

one of which is of older than the other belonging to the tertiary age. Further, since the younger granites and the ore deposits have close age relations as determined by their lead isotope ratios, the investigations are chiefly confined to these two geologic bodies. An attempt has been made to compare them with respect to their chemical composition of certain rock forming minerals, trace element contents of their mineral fractions and isotope abundances.

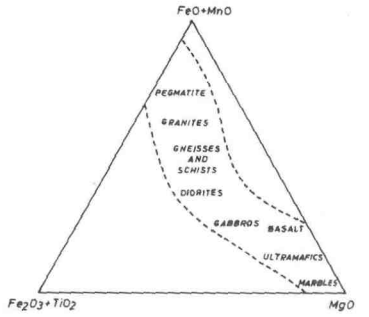
I. Chemical composition of biotites of host rocks and the younger granites

The biotites, derived from the mineralized zones in the altered wall rocks and also those from the younger granitic rocks have been chemically analysed. The biotites from the mineralized zone have significant amounts of FeO, MgO and K_2O, but are depleted in Al_2O_3 and Na_2O contents. They (Fig. 41b ; Table 42) show some similarity with the biotites of younger granitic rocks as far as their chemical composition is concerned.

The analytical results of the biotites derived from the mineralized wall rocks, unaltered rocks and the younger and older granitic rocks from the area are more or less comparable with the results obtained by Henrich (1946). (Fig. 41a).

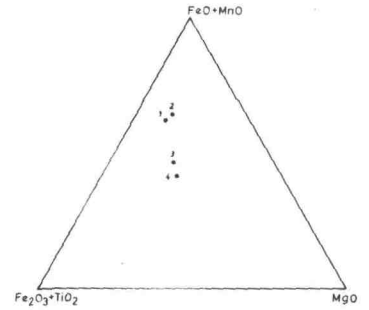
The biotite in the younger granites contains 16.31% FeO, 7.07% Fe_2O_3 + TiO_2 and 7.91% MgO, whereas the respective values of these constituents in the biotites obtained from the wall rocks are 18.40%, 5.83% and 8.95%. These values fall well within the range given for the constituents in the diagram for granites (Henrich, 1946). According to Deer et al.(1961), who summarized the principal results obtained by

a



VARIATION OF CHEMICAL COMPOSITION OF PHLOGOPITES AND BIOTITES WITH ROCK TYPE (COMPILED FROM DIAGRAMS OF HENRICH, 1946)

b



1- BIOTITE DERIVED FROM THE MINERALIZED ZONE AT PEKU COPPER DEPOSIT 2- BIOTITE DERIVED FROM YOUNGER GRANITIC ROCKS (TOURMALINE GRANITES) 3- BIOTITE DERIVED FROM OLDER GRANITIC ROCKS (DARJEELING GNEISS) 4- BIOTITE DERIVED FROM THE COUNTRY ROCKS, PEKU AREA

FIG. VARIATION OF CHEMICAL COMPOSITION OF BIOTITES DERIVED FROM THE COUNTRY ROCKS AND GRANITIC ROCKS AROUND DARJEELING HIMALAYAS

Fig.41

Henrich (1946), biotites in granites should have FeO content varying from 12 to 25%, Fe_2O_3 + TiO_2 generally less than 10% and MgO content upto 12%. The composition ranges of these three important constituents of biotites from the wall rocks adjacent to mineralised zones are well within those found in the biotites associated with granite. The biotites in these two different rock types may therefore have some genetic relation. Such a relation is possible only when the biotites in the granites as well as in the copper ore zone have a common source.

The biotites derived from the unaltered country rocks have 6.95%, 11.21% and 7.48% of FeO, Fe_2O_3+ TiO_2 and MgO respectively. It may be noted that FeO content is much lower and Fe_2O_3+ TiO_2 content higher than in the altered rocks. The discrepancies in the chemical composition of biotite from the unaltered rocks show that it cannot be correlated with the biotite derived from either the altered wall rocks or the younger granites.

The FeO and MgO contents in the biotites, derived from the older granitic rocks, are 12.30% and 13.23% respectively. The values are well within the range as recorded in these compounds in Precambrian granites (Deer et al., 1961). These values differ greatly from those obtained for the biotites derived from the mineralized rocks. This difference in composition may be considered as an evidence in support of the fact that the older granites have no relation with the wall rock alteration or ore deposition.

II. Distribution of copper, lead and zinc in biotite, hornblende, quartz and feldspars

Biotite, hornblende, quartz and feldspar were separated from the younger as well as the older granites. Separated mineral fractions from

the copper ore deposits are biotite, quartz and feldspar. Quartz was the only mineral separated from the lead-zinc ores.

A. Abundances of copper in biotite and hornblende (Figs. 43a & b).

1) Biotite

The copper contents of the biotites derived from the altered phyllites of Sikhip copper deposit adjacent to ore zone and from the unaltered rocks vary from 40-1500 ppm and 4-14 ppm respectively. The copper contents of the biotite derived from the altered slate wall rocks in Kalimpong area vary from 30-500 ppm, and from 3-9 ppm in the unaltered host rocks.

The biotite derived from the younger intrusive granites have a very high content of copper which ranges from 45-1500 ppm. But the biotites from older granites have a very low concentration of Cu in the range from 2-40 ppm.

2) Hornblende

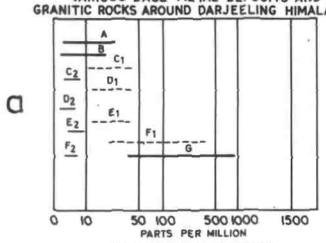
The analyses of hornblende show that the copper contents in the younger granites are higher than in the older granites and vary from 25-500 ppm. In the older granites it was found to vary from 2-20 ppm.

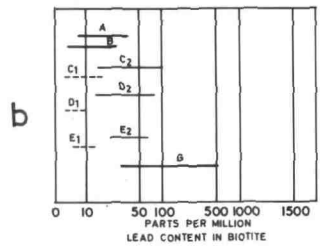
B. Abundance of lead in biotite, hornblende, feldspar and quartz (Figs. 43a, b).

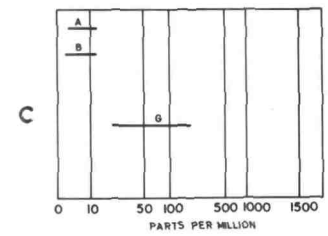
1) Biotite

Lead content of biotites from the altered wall-rocks at Sikhip, Peku and Kalimpong copper deposits vary from 4-20 ppm, 4-10 ppm and

LEAD CONTENT OF FELDSPAR, QUARTZ, BIOTITE AND HORNBLENDE FROM WALLROCKS AT VARIOUS BASE METAL DEPOSITS AND GRANITIC ROCKS AROUND DARJEELING HIMALAYAS



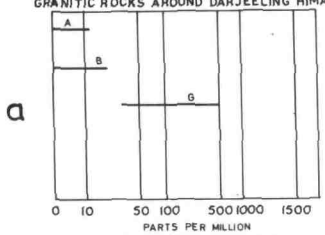


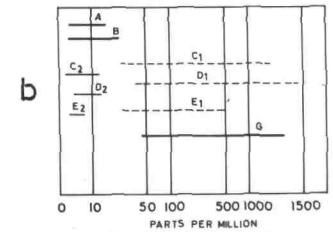


G=TOURMALINE-GRANITES—— (YOUNGER GRANITIC ROCKS)
A= BIOTITE GRANITE GNEISSES } OLDER GRANITIC ROCKS
B= HORNBLENDE GRANITE GNEISSES }
C_1 & C_2= WALLROCKS AT SIKHIP COPPER DEPOSITS
D_1 & D_2= WALLROCKS AT PEKU COPPER DEPOSITS
E_1 & E_2= WALLROCKS AT KALIMPONG COPPER DEPOSITS
F_1 & F_2= WALLROCKS AT RISHI LEAD-ZINC DEPOSITS
UNALTERED
ALTERED
GRANITIC ROCKS

Fig. 42

COPPER CONTENT OF HORNBLENDE AND BIOTITE FROM WALLROCKS AT VARIOUS BASE METAL DEPOSITS AND GRANITIC ROCKS AROUND DARJEELING HIMALAYAS

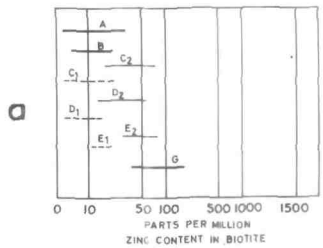


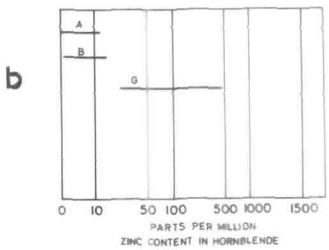


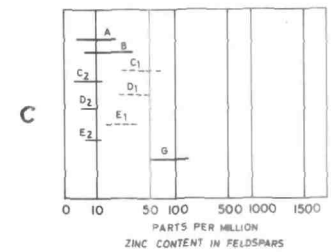
G=TOURMALINE GRANITES—— (YOUNGER GRANITIC ROCKS)
A= BIOTITE GRANITE GNEISSES } OLDER GRANITIC ROCKS
B= HORNBLENDE GRANITE GNEISSES }
C_1 & C_2= WALLROCKS AT SIKHIP COPPER DEPOSITS
D_1 & D_2= WALLROCKS AT PEKU COPPER DEPOSITS
E_1 & E_2= WALLROCKS AT KALIMPONG COPPER DEPOSITS
UNALTERED
ALTERED
GRANITIC ROCKS

FIG.

ZINC CONTENT OF BIOTITE, HORNBLENDE AND FELDSPARS FROM WALLROCKS AT VARIOUS BASE METAL DEPOSITS AND GRANITIC ROCKS AROUND DARJEELING HIMALAYS







G=TOURMALINE GRANITES—— (YOUNGER GRANITIC ROCKS)
A= BIOTITE GRANITE GNEISSES } OLDER GRANITIC ROCKS
B= HORNBLENDE GRANITE GNEISSES }
C_1 & C_2= WALLROCKS AT SIKHIP COPPER DEPOSITS
D_1 & D_2= WALLROCKS AT PEKU COPPER DEPOSITS
E_1 & E_2= WALLROCKS AT KALIMPONG COPPER DEPOSITS
UNALTERED
ALTERED
GRANITIC ROCKS

Fig.44

Fig. 43

5-18 ppm respectively. The concentration of lead in the biotites of unaltered rocks from the same localities is appreciably higher and varies from 14-100 ppm, 12-90ppm and 25-75 ppm, respectively.

Biotite in the older granites has 4-40 ppm of lead whereas the biotite in younger granite has a greater concentration of lead (35-500 ppm).

2) Hornblende

In the hornblende separated from older granites lead concentration is low (2-15 ppm) while in the younger granites hornblende has a higher concentration of Pb (20-225 ppm).

3) Feldspar and quartz

Generally, concentration of lead is higher in the feldspars and quartz derived from the altered wall-rocks than in those from the unaltered rocks. For example, the lead content in the quartz and feldspars obtained from the altered wall-rocks and the unaltered rocks which hosted the Pb-Zn deposits at Rishi varies from 30-400 ppm, and 2-7 ppm respectively. Lead contents in quartz and feldspars from the altered wall-rocks around the copper deposits at Sikhip, Peku and Kalimpong areas vary from 10-40 ppm, 11-45 ppm and 12-40 ppm respectively. On the other hand, lead concentrations in the feldspathic minerals from the unaltered rocks in these deposits vary from 3-9 ppm, 2-8 ppm and 4-10 ppm respectively. The same minerals from the older granites have 2-35 ppm of Pb, whereas those from younger granites show a very high concentration of Pb (40-900 ppm).

C. Abundance of zinc in biotite, hornblende, feldspar and quartz (Figs. 44a,b & c).

1) Biotite

Zn content like Pb records comparatively lower values in the biotites derived from the wall-rocks of the copper deposits at Sikhip, Peku and Kalimpong. Biotites from the altered host rocks of these copper deposits contain 3-30 ppm, 2-16 ppm and 12-28 ppm of Zn respectively. But Zn concentration in the unaltered host rocks was found to vary appreciably at Sikhip, Peku and Kalimpong from 20-90 ppm, 10-60 ppm and 30-100 ppm respectively. The zinc values in the biotites, derived from the older granitic rocks, vary from 2-40 ppm whereas its value in the biotites from the younger granites varies from 40-200 ppm.

2) Hornblende

Zn content in the hornblende from the older granites ranges from 2-20 ppm and in the younger granites, it varies from 25-500 ppm.

3) Feldspars and quartz

Generally zinc content like that of copper was found to be higher in feldspar and quartz derived from the altered wall-rocks as compared to its abundance in the same minerals from the unaltered rocks. In the quartz-feldspars derived from the altered wall-rocks of the copper deposits at Sikhip, Peku and Kalimpong it varies from 30-75 ppm, 30-50 ppm and 12-40 ppm respectively. Zn values recorded in feldspars and quartz from unaltered country rocks around these deposits vary from 2-15 ppm, 5-10 ppm and 5-12 ppm respectively.

The zinc content in the quartz and feldspars derived from older granites varies from 4-38 ppm and in those derived from the younger

granites, it shows higher values ranging from 50-225 ppm.

Discussion

According to Pauling (1960) the structure of biotite provides a number of sites where diadochic substitution may take place. Goldschmidt (1954) provided the rules for such substitution. De Vore (1955) stated that the minor elements in biotite may occupy lattice position in addition to other sites in the mineral such as admixed solid and liquid inclusions and as exsolution product. Further, according to him, "copper, like cobalt, nickel or chromium, does not logically follow the distribution trends", and "... important amounts of trace elements do not occupy regular lattice sites but, through the mechanism of absorption, occur on growth surfaces, imperfections, dislocations and various interfaces within the crystal".

Biotite derived from the altered wall-rocks, adjacent to ore zones, have a greater concentration of Cu than in those derived from the unaltered country rocks. Biotites from the younger intrusives granites show a more or less similar trend of copper concentration to those derived from the altered wall-rocks. The biotites derived from the older granitic rocks, however, show lower values of copper. Sandell and Goldich (1943), who studied the rare metallic constituents of some North American igneous rocks, observed that the average copper content of biotites in acid, basic and intermediate igneous rocks, varies from 149 ppm, 16 ppm to 38 ppm respectively. Biotites derived from the different source rocks may therefore show variation in their copper content.

The analytical results definitely show that the distribution trends of Cu, Pb and Zn in the biotites derived from the older and younger granites of the study area are different. The higher concentration trend of Cu, Pb and Zn in the biotites derived from the various lithologically different altered wall-rock and the younger intrusive granites indicates a genetic relation between the younger granitic bodies and the wall-rocks alteration. It was further supported by the fact that copper, lead and zinc contents have relatively higher concentrations in quartz and feldspar, derived from the same altered wall-rocks and the younger granites. However, the concentration trends of lead and zinc in the biotites derived from the altered wall-rocks of copper deposits are somewhat different from that of copper. In these rocks the lead and zinc contents in biotites are very poor although the metals have higher concentrations in the unaltered country rocks.

III. Isotope abundance in rocks and minerals

A comparison of the variation ranges of isotopes in the altered host rocks, the granitic rocks and some of their associated minerals has been found to be a useful guide to the source of the ore-forming fluids. It is well known that the isotopic compositions of the hydrothermal solutions differ in relation to their source and such differences can easily be used as a guide to the source of fluids from which mineral deposits are formed (Taylor, 1967). The δO^{18} isotopic values in the altered rocks as well as in minerals like quartz and muscovite, around the lead-zinc as well as the copper deposits have narrow ranges like those found in quartz and muscovite derived from the younger granites.

This is considered as a significant evidence supporting further the genetic association of the younger granites with the wall-rock alteration in both the deposits and the two silicate minerals associated with them. Such narrow isotopic ranges for the intrusive granitic rocks have been reported by various workers from many parts of the world (Figs.37 a,b). For example, Garlick (1964) has isotopically analyzed quartz from Boulder Batholith, Butte Copper deposit, for O^{18}/O^{16} ratios and found that the values are typical of magmatic hydrothermal bodies.

Isotopic ranges of S^{32}/S^{34} in ore minerals have been considered by various workers in different parts of the world as indications for close genetic relation between ore fluids and their probable source. According to Thode, MacNamara and Collins (1949) the isotopic compositions of pyrite bring to light the source of mineralisation. MacNamara et al. (1952) studied the isotopic ranges of sulphur from the sulphide minerals contained in igneous rocks of admittedly magmatic origin. The isotopic ranges of S^{32}/S^{34} in the ores or rocks of magmatic origin have always indicated narrow range (Jensen, 1959, 1962; Smirnov, 1968).

This is the first attempt to apply the sulphur isotope ratio of some sulphide minerals of the area for determining their range of values and the consequent source of mineralisation. The narrow spreads of S^{32}/S^{34} ratios in ore minerals like galena, sphalerite, chalcopyrite in some ore minerals, and also in pyrite from the ore zone and the adjacent wall rocks very much resemble the ranges determined in the ores associated with magmatic hydrothermal deposits (Figs.40a,b). It may, therefore, be stated that the nature of mineralisation of copper, lead and zinc was magmatic hydrothermal.

Various workers including Cannon et al.(1961), Rama Murthy and Patterson (1961), Kanasewich (1962), Moorbath (1962), Heyl et al. (1965), Brown (1962), Mitchell et al. (1971) have successfully utilized lead isotope data from the wall rocks of various ore deposits for genetic and geochronological purposes. The present author has made the first attempt to determine the isotopic composition of lead in galena from lead-zinc deposits and also in feldspars from the altered wall rocks of copper deposits and the younger granites (Table 26 , Fig. 45) with a view to throw more light on the source of the mineralizing solutions.

Lead ratios in the feldspars belonging to the altered zones are found to be similar to those occurring in feldspars derived from the younger granites. These lead ratios in feldspars (Table 26) are strikingly similar to those found in the galena occurring in the lead-zinc deposits of Rishi area. Therefore, the isotopic similarity of lead in galena, feldspars in the wall-rocks as well as in the granitic rocks strongly suggests their common source. This view is further supported by a similar age of radiogenic lead in galena from lead-zinc deposit, in feldspars belonging to younger granites, and from the altered wall rocks of copper deposits. The age is found to be 20 $\pm$ 10 million years (with an average of 13 m.y.).

IV. Temperature of ore deposition

Some evidences are also available in support of the probable temperature of the ore fluids which has a direct bearing on the source of the deposits. Isotopic values of δO^{18} and assemblage of certain

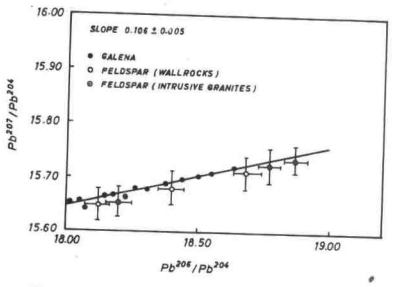


FIG. LEAD ISOTOPE ANALYSIS OF GALENA AND FELDSPARS FROM THE BASE METAL DEPOSITS AROUND DARJEELING HIMALAYAS

Fig. 45

TABLE - 26 Lead isotope ratios for lead in galena, and potash feldspars.

No.	Nature of sample	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
1	Galena : Rishi area	18.14	15.66	38.45
2	Galena : Rishi area	18.55	15.72	38.67
3	Galena : Rishi area	18.41	15.70	38.94
4	Galena : Rishi area	18.45	15.68	38.66
5	Galena : Rishi area	18.49	15.70	38.65
6	Galena : Rishi area	18.50	15.71	38.50
7	Galena : Rishi area	18.12	15.65	38.66
8	Galena : Rishi area	18.22	15.64	38.62
9	Galena : Rishi area	18.25	15.69	38.55
10	Galena : Rishi area	18.30	15.68	38.50
11	Galena : Rishi area	18.05	15.64	38.58
12	Galena : Rishi area	18.04	15.66	38.63
13	Galena : Rishi area	18.00	15.65	38.62
14	Potash-feldspar : from Wall-rocks, Peku copper deposits	18.67	15.70	38.95
15	Potash-feldspar : from wall-rocks, Peku copper deposits	18.40	15.68	38.68
16	Potash-feldspar : from wall-rocks, Peku copper deposits	18.12	15.65	38.65
17	Potash-feldspar : from intrusive granites	18.75	15.71	38.81
18	Potash-feldspar : from intrusive granites	18.85	15.72	39.16
19	Potash-feldspar : from intrusive granites	18.20	15.64	38.55

minerals have mainly supplied such evidences.

A. Isotope ratios

Experiments on the use of oxygen isotopes as geothermometers have proved that oxygen isotope geothermometry is possible for the minerals like quartz, calcite, muscovite, alkali feldspars and water (Bigeleisen and Mayer, 1947; Urey, 1947; Silverman, 1951; Taylor and Epstein, 1962, 1963; O'Neil and Clayton, 1964; Taylor and Coleman, 1965; Clayton, O'Neil and Mayeda, 1966; O'Neil and Taylor, 1966; Taylor, 1967; Sheppard, Nielson, and Taylor, 1971; Pinckney and Rye, 1972). According to Taylor (1967), "Oxygen isotope geothermometers will have wide application in the field of hydrothermal mineral deposits because the isotopic fractionations are so much larger in the range of 100°- 400°C than at higher temperature ranges, and it should be possible to obtain temperatures of formation of hydrothermal minerals to within ± 5°C if equilibrium is commonly established". Hall and Friedman (1969) have suggested that patterns of δO^{18} values in the altered rocks reflect the presence of a temperature gradient in the wall-rock during alteration.

An attempt is made here to correlate the results obtained from the study area, with the data from known assemblages to see where the δO^{18} ratios of quartz and muscovite fall and thus to use the oxygen isotopes as geothermometers of the ore deposits. A comparison of the isotopic compositions of the quartz, calcite, and dolomite from the ore zone as well as the altered zone in lead-zinc deposits with the standard and known values indicates that the temperature of the ore fluids falls within a range of 150°C to 250°C ± 25°C. Similarly, the

δO^{18} values obtained from the altered wall rocks and the ore zone in the copper deposits, and also the δO^{18} variations in the quartz in the Pb-Zn deposits closely agree with the standard and known ranges and indicate that the temperature of ore fluids ranged from 185°C to 350°C.

B. Mineralogical assemblages

The mineralogic work done was not specially oriented towards the geothermometric investigations. Temperatures of ore deposition may also be determined by the study of mineral assemblages (Park Jr. and MacDiarmid, 1964). Some of the evidences available are given below:

a) The total absence of such high temperature silicate minerals in the host rocks as wollastonite, tremolite, forsterite, periclase, etc. suggest that the upper limit of the temperature was not perhaps more than 400°C or nearly so.

b) Since most of the copper ore deposits do not have associations of pyrhotite or arsenopyrite, the temperature of the ore-bearing fluid was rather moderate.

The association of pyrite with marcasite in these deposits is also a significant feature. Recent experimental studies on pure Fe-S-O system in dry have shown that the formation of pyrite is possible with the upper stability limit at 743°C, but marcasite was not formed. Kullerud (1960, 1961) prepared mixture of phases in Fe-S-O-H system, and maintained temperatures with a maximum of 432°C ± 30°C. Upto this temperature both pyrite and marcarite were formed but above this temperature only pyrite continued to form.

Chapter IX

SUMMARY AND CONCLUSIONS

The main purpose of the present investigation has been to study the nature of base metal mineralization in the Darjeeling Himalayas, with particular reference to the geochemistry of the ore deposits and the associated country rocks. Considerable attention was paid to deal with the stratigraphy, structure and petro-mineralogy of the various rock formations of the area, and also the mineralogy of ore deposits.

A considerable time was spent in the field in order to construct geological maps of the area and some of the ore deposits, in addition to collecting a large number of samples required for petrological and geochemical studies. A summary of this investigation and the conclusions arrived at, are presented as follows:-

1. The base metal deposits of Darjeeling Himalayas are essentially of copper, lead and zinc. They occur in a variety of metasedimentary rocks belonging to the Daling and Baxa Series of Precambrian to Cambrian age. The other important rock groups, encountered in the area, are Darjeeling Series (Precambrian), Damuda Series (Lower Gondwana), and Siwalik System (Miocene). Among the igneous rocks which are found to be definitely intrusive, mention may be made of some post-Gondwana

basic and ultrabasic dykes and sills, and tertiary granites.

The stratigraphic sequence of the various rock types of the area has been determined as follows:-

Alluvium	Sand and gravel	Recent to sub-recent
Old alluvium	High level terraces of sands and gravels.	
Siwalik System	Sandstones, mudstones, clay, shale and pebble beds with thin bands of limestones and lignites.	Miocene
---------- Thrust ----------		
Post-Gondwana intrusives	Basic and ultrabasic sills and dykes	Jurassic
Damuda Series (Gondwanas)	Sandstones, carbonaceous shales, slates, pebble and boulder beds, and thin coal seams	Permian
---------- Thrust ----------		
Baxa Series	Dolomites, limestones, dolomitic limestones, phyllites and quartzites (host rocks of lead-zinc and copper deposits)	(Cambrian ?)
---------- Tectonic contact ----------		
Daling Series and Darjeeling Series	Phyllites, slates and schists with minor bands of quartzites (host rocks of copper deposits) Granite-gneisses, etc.	Precambrian

2. Due to inversion of the sequence of Darjeeling and Daling rock Series in the area, the Darjeeling gneisses overlies the less metamorphosed Daling Series. There is no visible stratigraphic break between

the two rock series. Phyllites, slates, schists and quartzites of the Dalings are conformably succeeded by the gneisses belonging to the Darjeeling Series through a zone consisting of garnetiferous biotite-schists between the two series. The sulphide mineralization is largely restricted to the Daling Series although a few sporadic sulphide occurrences have been reported from near the contact of the two series. The lead isotope ratios in the feldspars as well as in the whole rock samples of the Darjeeling gneisses indicate that their age is 1760 ± 60 million years. However, the age of metamorphism of the Darjeeling gneisses is much younger and vary from 10 to 25 million years, according to the potassium-argon method of age determination.

3. The Baxa Series, which overlies the older Daling Series, probably with a tectonic contact, is composed mainly of limestones and dolomites with occasional lead-zinc deposits and a few small occurrences of copper. Bands of slates, phyllites and quartzites are occasionally intercalated with these rocks. Limestones having stromatolites, belonging to genus Collenia, are also found associated with the Baxa Series at only two localities. The presence of this algal limestone in the Baxas supports the existing view that the age of Baxas may be from upper Precambrian to Cambrian. It has also been possible to correlate the dolomitic limestones of the area with the Calc-zones of Pithoragarh and Bageshwar in the Western Himalayas, where also such algal limestones occur.

4. The sedimentary rocks, which consist of pebble beds, sandstones, and carbonaceous shales with occasional coal seams, rest against the

Baxas and Dalings with a thrusted contact. They belong to the Damuda Series of the Gondwana System, and form a tectonic window in the Ranjit valley. The Siwalik rock formations are also encountered in the area, south of the 'Main Boundary Fault'. They are generally composed of soft and massive sandstones with interbedded nodules of marl and clay.

5. The petrographic study of the host rocks of lead-zinc and copper ores and other rock types of the area was made in order to have an idea of their mineralogical composition and textural characters. The altered and unaltered host rocks of the ores have been studied separately. A comparative study of the petro-mineralogical characters of the altered and the unaltered carbonate rocks, with which the lead-zinc ores are associated, indicates that the altered rocks differ considerably from the unaltered ones with regard to their mineral composition, grain size and texture. The altered carbonate rocks are highly silicified and dolomitized to a large extent. The increase in grain size and porosity of the rocks is very conspicuous. The texture was also changed from micritic in the case of unaltered to porphyrotopic in the altered carbonate rocks.

6. Most of the host rocks, within which the copper ores occur, show considerable variation in their petrographic characters. Usually, the rocks are Daling phyllites and schists, composed largely of quartz, chlorite, biotite and sericite. Tourmaline, garnet and plagioclase feldspars are the minor constituents. Chert and jasperiod are the common associations. The carbonates are sub-ordinate in amount. The

unaltered phyllites and schists have the usual mineral composition consisting of muscovite, chlorite with abundant quartz. Jasperiod and chert are totally absent. Chlorite occurs in various proportions and muscovite appears fresh. There is no sign of leaching of the mineral grains in these rocks. Garnet commonly occurs as porphyroblasts. The petrographic characters of other non-mineralized rock types such as mylonitized biotite-quartz schist of the Daling Series, the Damuda sandstones, epidiorites and dolerites, have been briefly described. The important mineral constituents of the Darjeeling granite-gneisses are quartz, feldspar, biotite, garnet, muscovite, sillimanite, epidote, etc. Three varieties of the gneisses namely, biotite-gneiss, garnetiferous-biotite-muscovite gneiss and sillimanite-biotite gneiss have been identified.

7. Generally, the Darjeeling and Daling rock series were subjected to regional metamorphism which was probably initiated during the tertiary tectonic movements in the Himalayas. Contact metamorphism in these rocks has been conspicuously effective only around the larger bodies of igneous intrusives and the sulphide ore deposits. The gradual increase of the grade of regional metamorphism from the underlying Daling slates, phyllites, schists, etc. to the overlying Darjeeling gneisses is a classic example of the reversed order of metamorphism of the Precambrian rocks encountered in the eastern Himalayas. The chemical compositions of the Darjeeling gneisses and the Daling phyllites, schists, etc, suggest that their original constituents were probably pelitic sediments with some associations of siliceous and carbonate

materials. The chemical composition of the Baxa limestones shows that they represent a calcareous sedimentary facies.

8. The general structural pattern of the metasedimentary rock formations of the area indicate that they were subjected to intense deformation and dislocations, most of which were related to the tertiary orogenic movements in the Himalayas. The Darjeeling and the Daling Series form a part of the major recumbent fold. There is practically no evidence of any major thrust at the contact of the two series, as some of the earlier workers have suggested. The thrust between the Baxa and Damuda Series and also that between the Damuda Series and the Siwaliks are quite distinct in the area. There are a number of prominent faults which have been located at several places in the area. Some of them have not only controlled the physiographical features but also the localization of the important mineral deposits of the area. Most of the rocks belonging to Darjeeling, Daling and Baxa series are highly folded and jointed. The general trend of the major fold axes is NW-SE, and sometimes NNW-SSE. They are generally pitching folds overturned towards the south. The Tista and the Rajnit valleys are more or less controlled by the axial trends of two such major anticlinal folds. The Darjeeling gneisses form a synclinorium from north of Tindharia near Kurseong to the north of Darjeeling. The strike of this synclinorium is NNW-SSE.

9. As far as possible the present as well as the ancient workings of copper and lead-zinc deposits of the area were taken into consideration for investigating the nature and modes of occurrence of the ore deposits.

Generally, the deposits are of three types, namely, 1) vein and stringer, 2) disseminated and 3) massive. The vein and stringer type of deposits is the most common. They are usually localized in the fracture and shear zones. Often they cut across the foliation or bedding planes of the country rocks. The disseminated ores commonly occur in the highly silicified rocks and particularly in those which are quartzose, filling partly the inter-granular spaces and partly replacing their mineral constituents. The less common type of the massive ore is generally located in widely gaping and fracture zones formed due to shearing.

10. The lead-zinc deposits, which are associated with the Baxa dolomitic limestones, occur along certain shear zones. There are two mineralized zones namely, upper and lower, in the Rishi area. The Pb-Zn lodes are lensoid in shape and contain a fair concentration of galena with subordinate amounts of sphalerite and pyrite. The deposits are structurally controlled and generally disposed parallel to the major shear planes.

11. The copper occurrences are mostly reported from the slates, phyllites, schists and quartzites belonging either to Daling or Baxa Series. Sometimes they are associated with rare earths and thorium minerals. The important copper deposits occur at Peku, Legship, Sikhip, Rohtak Khani, Jagdum, Kalimpong, Pachikhani and Rangpo. In most of the localities the ores are of vein type and invariably associated with lenticles of quartz veins. There are a few instances of massive and disseminated ores. The primary controls on majority of the deposits

are such structural elements as schistosity, shear planes and fracture cleavages of the country rocks. The other type of quartz veins, which has white and semi-vitreous quartz, are generally barren.

12. The copper ore samples, which were collected from the various deposits, have been analysed by the neutron activation method for determining their tenor. Barring a few clean samples, the average grade of the ores is low and they contain less than 1 per cent of copper.

13. Mineralogical study of some selected polished ore specimens under reflected light led to the identification of chalcopyrite, chalcocite, pyrrhotite, pyrite, arsenopyrite, galena, sphalerite and bismuthinite as hypogene minerals; and covellite, chalcocite, enargite, malachite, azurite and limonite as supergene minerals. A few other supergene minerals like anglesite, cerussite, dundasite, rozenite, pyromorphite and mimetite have been identified by their characteristic powder pattern in X'-rays. Pyrite was found to be the common mineral in the copper and lead-zinc deposits. It is often associated with marcasite. Arsenopyrite and pyrrhotite have been found only in the ore samples derived from Rangpo, Peku and Pachikhani mines. Galena and sphalerite, which are the common ore minerals in lead-zinc deposits, are sometimes present as minor constituents in the copper ores. The intense deformation of galena crystals in the lead-zinc ores of Rishi is a very characteristic feature. Bismuthinite is a very rare constituent of the copper ores.

14. The mineral assemblages of the copper ores are 1) pyrite-arsenopyrite-pyrrhotite-chalcopyrite, 2) pyrrhotite-chalcopyrite-

sphalerite-galena, 3) pyrite-chalcopyrite-covellite-chalcocite, and 4) sphalerite-galena-bismuthinite. Lead-zinc ores are represented only by the galena-sphalerite assemblage. The textural features of these ore assemblages have been also studied with a view to determine the paragenetic sequence of the ore minerals, which is given in the table 15 .

15. The study of geochemical behaviour and abundance of some 16-20 trace elements in the host rocks of copper as well as of lead and zinc deposits, and also in some of their hypogene and supergene minerals proved to be very useful in the present investigation. The abundances of the trace elements namely, Zr, V, Ni, Ag, Zn and Pb are from moderate to traces in the copper deposits as well as their altered and unaltered host rocks. The concentrations of Sr, Ti, Cr and As, which are appreciably high in the ore zones, gradually decrease as the altered and unaltered rocks are approached. The ore zones as well as the altered host rocks have very low concentrations of Ga, Ge, Sn and Bi, which are characteristically absent in the unaltered rocks. Among the trace elements, which are associated with the lead-zinc deposits and their host rocks, Sr, V, Co and Cu generally have moderate to very low concentrations. Cr, Cd and As have a decreasing concentration trend from the ore zone through the altered to unaltered host rocks. The concentrations of Ba, Ti, V, Ni and Ag are higher in the unaltered rocks than in either the altered rocks or the ore-zones. Ga, In, Ge and Sn are present in traces in the ore zone, but they are completely absent in the host rocks.

16. A comparative study of the trace elements, which are commonly present in the two different types of ore deposits and their respective

host rocks indicates that majority of the trace elements have similar concentration trends. A few other trace elements, however, have strikingly different concentration trends in the two deposits. Obvervations, based on this study, strongly suggest that the copper ores have some genetic relation with the lead-zinc ores.

17. Strikingly similar abundance of some trace elements, which are common in the pyrites derived from the copper ores as well as the lead-zinc ores, strongly suggest that the pyrites have intimate genetic relations. Chalcopyrite and pyrrhotite have much more higher concentration of Co, Ni, Mo, Ti and As than galena and sphalerite have. The limonites, which commonly occur in the copper and lead-zinc deposits, have generally the highest concentrations of Pb, Ti, Cu, Zn and Ag. Next in abundance in the limonites are Sn, Cd, Cr, Sb and Ba. Pb and Zn recorded considerably high concentrations in the malachites derived from both copper and lead-zinc deposits.

18. A study of the alterations of wall rocks revealed many interesting facts regarding the nature and sequence of alteration besides the source and temperature of mineralisation. The physical, mineralogical and chemical changes due to alteration of the lead-zinc host rocks have been very conspicuous. Primarily, the rocks were dolomitized. The physical alterations consisted largely of change in colour, texture, porosity and permeability of the rocks, in addition to their high silicification. Dolomite, calcite and to a certain extent, talc are the chief minerals involved in changing the mineralogy of the altered carbonate rocks. A distinct change in the chemical composition of the

country rocks from the ore-zone through the altered to the unaltered rocks has been observed, particularly with respect to their Ca/Mg ratio, SiO_2 and CO_2 contents.

19. In the case of the host rocks of the copper deposits, distinct changes in their physical, mineralogical and chemical characters have been observed although they are not as conspicuous as in the case of the carbonate rocks. The wall rocks, consisting of phyllites, schists, slates, etc., have been generally chloritized and sericitized. There was also a change in colour of the rocks from the dark grey to light grey. Mineralogical changes were largely brought about through the processes of biotitization, chloritization and sericitization. In certain cases silicification and slight dolomitization were also recorded. The chemical changes due to alteration of the various lithological units have been rather complex. Silica, magnesia, potash, iron oxides, sulphur dioxide and water are the important additions to the altered rocks, and lime, soda, alumina and phosphorous pentoxide are those which are removed from the system. The sequence of alteration of the wall rocks prior to the deposition of the copper ores has been as follows:

Dolomitization-silicification-biotitization-chloritisation and sericitisation.

20. The isotopic values of δO^{18} and δC^{13} in the host rocks of lead-zinc as well as of the copper deposits have been determined. The S^{32}/S^{34} ratio in some sulphide ore minerals have also been determined. The δO^{18} and δC^{13} values in the unaltered limestone fall within a range which indicates that it is of marine origin. But the ratios of these

isotopes generally have a tendency to decrease gradually from the unaltered through altered limestones to the ore zone rocks. The δO^{18} variation reflects a thermal gradient whereas δC^{13} values indicate that a large amount of carbon was involved during the alteration.

In the case of rocks associated with copper deposits the isotopic values of δO^{18} and δC^{13} in quartz and muscovite gradually decrease from the unaltered rocks to the ore zone. Such a change in the isotopic ratios of δO^{18} and δC^{13} is also indicative of a thermal gradient in these rocks during alteration. The S^{32}/S^{34} ratio in some of the sulphide ore minerals, which are associated with copper and lead-zinc deposits, show a very narrow range. Pyrite, which has a wide range of distribution from the unaltered rocks to the ore zone indicates that its range of S^{32}/S^{34} ratios is minimum in the ore zones. The range is very much similar to that found in the case of hydrothermal ore deposits from various parts of the world.

21. For probing precisely the source of the sulphide mineralisation, a study of the relative abundance of the important chemical constituents of some ferromagnesian and feldspathic minerals of the older Darjeeling granite-gneisses, the younger tertiary granites and also of some host rocks of the ore deposits, has been made. Biotite, hornblende, quartz and feldspars, which are the common minerals in some of these rocks, have been separated and analysed for this purpose. The variation ranges of FeO, $Fe_2O_3 + TiO_2$ and MgO in biotites from the wall-rocks of some copper ore deposits, are more or less the same as those found in biotites from the tertiary granites. Since the variation ranges of the constituents

also fall well within the variation diagram for granites, as shown by Heinrich (1946), it is reasonable to associate genetically the biotites in the younger granites with those which occur in the wall-rocks.

Copper in hornblende from the younger granites occurs in much greater abundance than that present in hornblende associated with the older granites. Like copper, lead and zinc concentrations in biotite and hornblende from the younger granites are appreciably higher than in the same minerals separated from older granites. Although quartz and feldspars have very low concentration of Cu, Pb and Zn as compared to biotite and hornblende, yet these feldspathic minerals from the younger granites recorded relatively higher values for Cu, Pb and Zn than in those derived from the older granites. Generally, the biotites derived both from the altered wall rocks of copper and the younger granites have a higher concentration of copper than in those separated from the older granite-gneiss. Accordingly, as far as the abundance of base metals in the rock-forming minerals is concerned, the younger granites and the altered wall rocks may be geochemically correlated.

Further, the range of isotopic values of δO^{18} in quartz and muscovite derived from the younger granites was found to be as narrow as that obtained in the altered wall-rocks of the ore-deposits as also in some associated minerals like quartz and muscovite. On applying the knowledge of sulphur isotopic ratios of some sulphide ore minerals, including pyrite, it was found that S^{32}/S^{34} ratios in the ore-minerals derived from copper, lead and zinc ores and also from the adjacent wall rocks fall within a narrow range which is a characteristic of hydrothermal

deposits.

22. The radiometric age of feldspars, separated from the younger granites and the altered host rocks of copper ores, has been determined from their radiogenic lead isotopes and it was found to be 20 ± 10 million years. Also, the determinations of the radiogenic lead isotopes in galena from lead-zinc deposits, indicate that galena has more or less the same age range as that of feldspars in granites and wall-rocks.

23. The δO^{18} values in quartz and muscovite from the copper deposits; and quartz, calcite and dolomite from the lead-zinc deposits, have been determined in order to have an idea of the probable temperature gradient of the mineralizing solutions. A comparison of δO^{18} values with those which are considered as the standards, indicates that the temperature of the ore-fluids was moderately high. Further evidence in support of this temperature gradient is available from the assemblage of certain index minerals in the host rocks as well as the ore deposits.

From the foregoing observations it is reasonable to infer that the nature of copper, lead and zinc mineralisation in the study area was magmatic hydrothermal and that the temperature of the ore fluids was moderately high. As a reasonable explanation for the close geochemical and geochronological relations between the tertiary granites and the ore deposits including their altered wall-rocks, it may be stated that the former probably served as a source of some of the elements involved in the deposition of the sulphide ores and the alteration of their wall-rocks.

EXPLANATION OF PLATES

Field Photographs

PLATE I

A spectacular view of the southeastern face of the Kanchenjunga peak (28,146 ft) of the Himalayas. Granite intruding the metasedimentary sequence of Darjeeling Himalayas.

PLATE II

The Kanchenjunga range seen from the southeast.

PLATE III

Daling series (1) overlying the Darjeeling gneiss (2) - a normal sequence in the Tista valley north of Darjeeling Himalayas. Mount Kanchenjunga is seen in the background.

PLATE IV

Fig. 1 Fractured and folded Daling phyllites intercalated with quartzites near Kalimpong copper deposit.

Fig. 2 A pegmatite vein in Darjeeling gneiss near Darjeeling.

Fig. 3 Cross jointing in Daling quartzites intercalated with phyllites near Tendong.

PLATE V

Fig. 1 Basal conglomerates (Damudas) near Tindharia.

Fig. 2 Pebbly slate (Damudas) showing rafted clasts near Tindharia. In the left hand corner a rafted granite pebble is shown enclosed within bedding laminae.

PLATE VI

Fig. 1 Namchi town on the Gondwana rocks. Faulted contact between the Dalings (1) and the Gondwanas (2) on the southern slopes of Tendong hills.

Fig. 2 A portion of the northeastern limit of the Gondwana tectonic window as seen from north of Namchi.

PLATE VII

Fig. 1 A portion of the northwestern limit of Gondwana tectonic window in the Ranjit valley as seen from southeast of Sikhip. The faulted contacts between Gondwanas (1), Baxas (2) and Dalings (3) have also been shown.

Fig. 2 The course of Tista river following the axial trace of an anticline formed in the Daling Series, east of Darjeeling Hills.

Fig. 3 Darjeeling Series (1) overlying the Daling Series (2) - a reversed sequence north of Legship.

PLATE VIII

Fig. 1 A section of the Ranjit valley, showing a fault between Gondwanas (1) and Baxas (2), and the fault-scarps on both sides of Ranjit rivers. The copper mines (3) on the eastern side of Ranjit river are seen here.

Fig. 2 Faulted contact of Gondwanas (1) with Baxas (2) on the Nayabazar-Rishi road near Sikhip.

Fig. 3 Ranjit valley as seen from south of Sikhip. Gondwanas (1) faulted against Baxas (2).

PLATE IX

Fig. 1 A fault scarp near Sikhip on the Ranjit valley. Baxas (1) with lamprophyre sills (2) are seen. The copper mines (3) are located at the top of the wall-like scarp face.

PLATE X

Fig. 1 Darjeeling gneiss (1) overlying the Daling Series (2) - a reverse sequence northeast of Rabang La Pass.

Fig. 2 A fault scarp in Daling phyllites north of Darjeeling.

Fig. 3 Darjeeling Series (1) underlying the Daling Series (2) - a normal contact near Singheeke. Kanchenjunga range is in the background.

PLATE XI

Fig. 1 A recumbent fold in phyllites and slates (Dalings) near Pachikhani copper mines.

Fig. 2 Well-bedded limestones within the Baxas (1), locally folded and dragged near the thrusted contact with Dalings(2) on the Nayabazar-Rishi road, north of Jorthang near a bridge over the Ranjit river.

Fig. 3 Jointing in sandstones interbedded with shales (Damudas) near Namchi.

Photomicrographs of Thin Rock Sections

PLATE XII

Fig. 1 General texture of barren micritic limestones. x 18

Fig. 2 Development of dolomite (dark grey) from fine calcite (light grey). x 18

Fig. 3 Dolomite (dark grey) developing from anhedral fine calcite. x 18

Fig. 4 Replacement of both calcite (light grey) and dolomite (dark grey) by jasperoid (white). x 18

PLATE XIII

Fig. 1 Euhedral dolomite developing from anhedral calcite (crossed nicols). x 18

Fig. 2 Replacement of both calcite (light grey) and dolomite (dark grey) by Jasperoid (white). x 18

Fig. 3 Porphyrotopic texture of dolomitic limestones adjacent to the mineralized zone. x 18

Fig. 4 Jasperoid vein (white) with galena (black) replacing both calcite and dolomite. Note some subrounded grains of dolomite and calcite in jasperoid. x 18

PLATE XIV

Fig. 1 Galena-jasperoid association. Note the penetration of galena (black) into jasperoid (white) and dolomite (light grey). Also note some sub-rounded grains of jasperoid within the galena. x 18

Fig. 2 General texture of lamprophyre (crossed nicols). x 18

Fig. 3 Opaque minerals (pyrite-chalcopyrite) occupy the intergranular space and fractures in schists. x 18

Fig. 4 The automorphic tendency of jasperoid (white) against opaque ore-minerals (black) in phyllites. x 18

PLATE XV

Fig. 1 Loosely compacted quartz grains with jasperoid in quartzites. The opaque minerals (black) occupy the fractures and the intergranular spaces. x 18

Fig. 2 Pyrite-chalcopyrite (black) occupy the vugs and intragranular spaces in slates (crossed nicols). x 18

Fig. 3 Pyrite-chalcopyrite (black) - jasperoid (white) association in phyllites. Note the opaque minerals occupy the vugs and the fractures (crossed nicols). x 36

Fig. 4 Pyrite-chalcopyrite (black)-jasperoid (white) occupying the open spaces and fractures in schists (crossed nicols). x 36

PLATE XVI

Fig. 1 Jasperoid (white)-pyrite-chalcopyrite and other Cu-Fe sulphides (black) along cleavage and fracture planes in phyllites. Note the alteration of biotite to chlorite and the sericitization of muscovite (crossed nicols). x 40

Fig. 2 Folded, puckered and mylonitized schists. Note the dragging along the planes of cleavage. x 40

Fig. 3 Silicified slate. Note the alteration of biotite to chlorite, and the association of distinctly coarser jasperoid grains with the veins of iron and copper sulphides (black) along the cleavage and fracture planes of the rock section (crossed nicols). x 40

Fig. 4 Epidiorite showing blasto-ophitic texture. Chlorite encloses prismatic crystals of epidote and some plagioclase. x 100

Fig. 5 Epidiorite showing the association of hornblende, epidote and sphene. x 100

PLATE XVII

Fig. 1 Medium grained altered dolerite showing typical ophitic texture. x 40

Fig. 2 Metabasite showing schistose texture (crossed nicols). x 40

PLATE XVIII

Fig. 1 Poorly sorted quartz wacke sandstones. Subrounded to subangular grains of quartz, of widely varying sizes, set in a matrix of mica and cryptocrystalline quartz.(Crossed nicols). x 100

Fig. 2 Brecciated quartzites with variable sizes of angular fragments of quartz.

Fig. 3 Garnetiferous schists. Note the alteration of biotite to chlorite, and the association of jasperoid (white) with the veins of copper-iron sulphides (black). (crossed nicols). x 80

PLATE XIX

Fig. 1 Biotite with hornblende in biotite granite. '(crossed nicols). x 80

Fig. 2 Oligoclase in biotite granite showing albite twining. (Crossed nicols). x 80

Fig. 3 Micro-folds and fracture cleavage in slates. Jasperoid (white) and copper-iron sulphides (black) are distributed along the fracture planes (Crossed nicols). x 80

Photomicrographs of Polished ore specimens

PLATE XX

Fig. 1 Euhedral crystals of pyrite (Py) show mutual boundary relation with pyrrhotite (Prh). x 160

Fig. 2 Fractured pyrrhotite grains in pyrite-pyrrhotite-chalcopyrite ore assemblage. x 35

Fig. 3 Irregular veins and vugs of chalcopyrite in vein quartz. x 90

Fig. 4 Intense deformation of galena is indicated by its folded cleavage traces. x 35

PLATE XXI

Fig. 1 Sphalerite (Sp) replacing chalcopyrite (Cp) formed in the intergranular spaces of pyrrhotite (prh). x 160 Oil emersion.

Fig. 2 'Mesh structure' formed by the reticulated veins of chalcocite in chalcopyrite. x 35

Fig. 3 Enargite (En) replacing pyrite (Py) along grain boundaries. Relicts of two unreplaced pyrite grains in enargite may be seen in the figure. x 160 Oil emersion.

Fig. 4 Arsenopyrite (Asp) is being partly replaced by pyrrhotite (prh). x 160 Oil emersion.

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PERSONAL VITAE

I was born in a landlord's family in Budaun, Uttar Pradesh, India, where my early schooling took place. I obtained Master's degree in Geology from the Aligarh Muslim University, Aligarh, and joined as a Scientific Officer in the Atomic Minerals Division, Department of Atomic Energy, Government of India. I carried out various important assignments given by the Department for mineral exploration in Himalayas.

I had an opportunity of working with various leading scientists in different research projects sponsored by UNESCO and IAEA (International Atomic Energy Agency) outside India. I was sent on deputation to Afghanistan by the Government of India, where I worked on various important mineral deposits.

While working in the Himalayas, I faced many times different problems related to the mineralization, which gradually inspired me to take up this research problem.

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PLATE I

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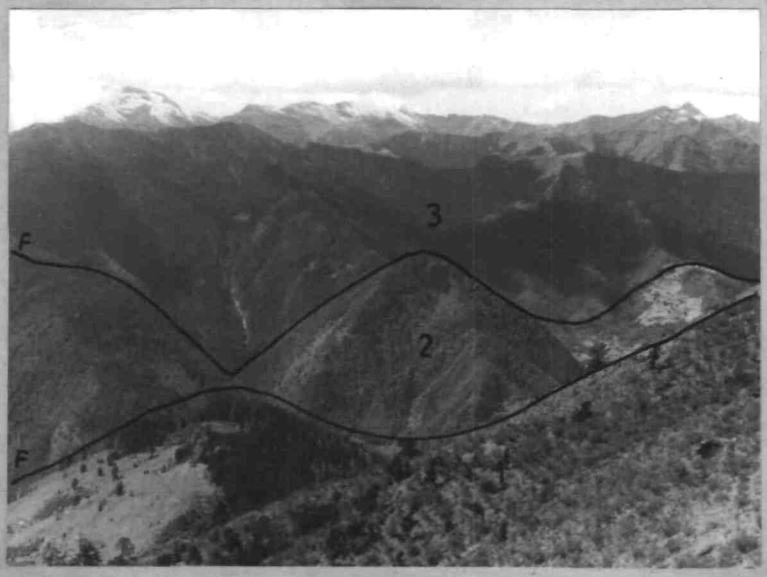
PLATE VII



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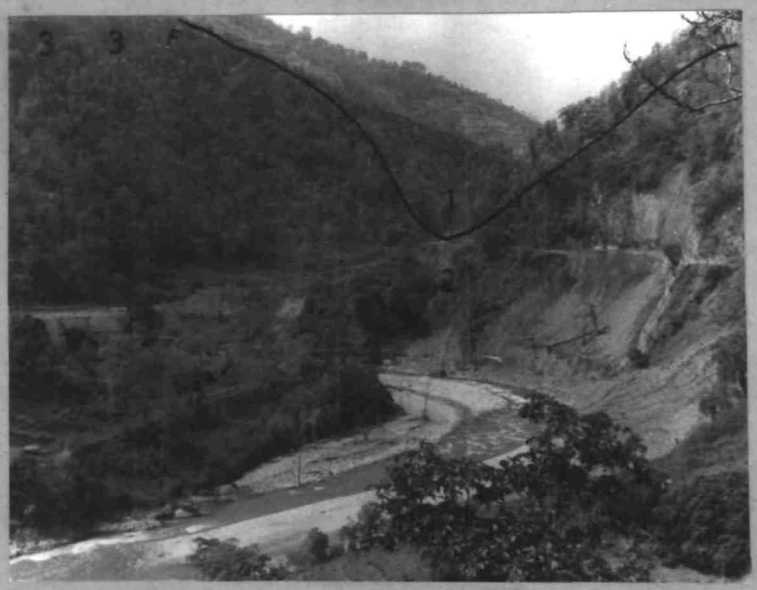

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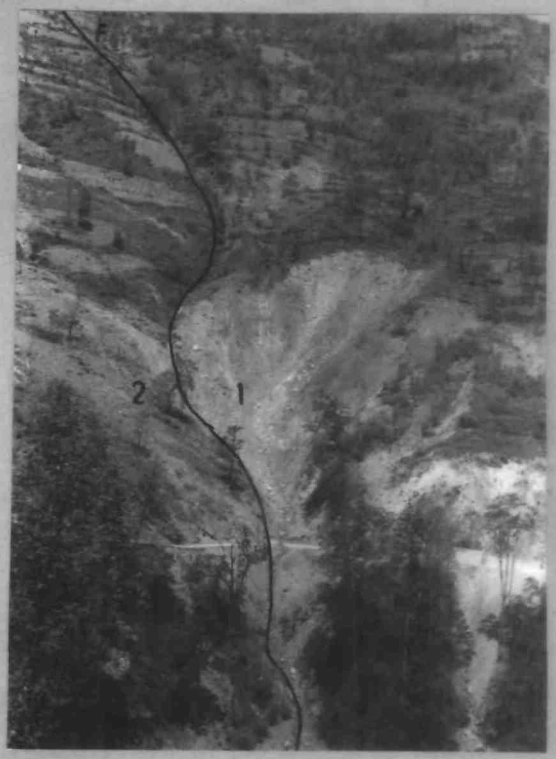

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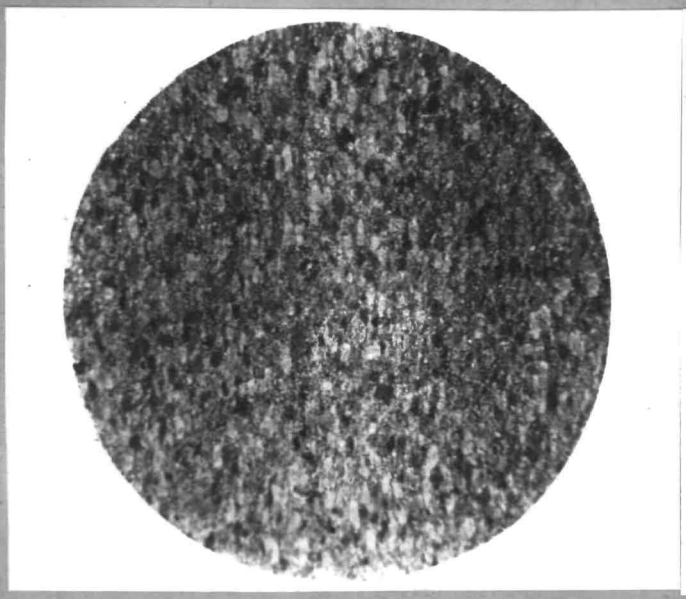

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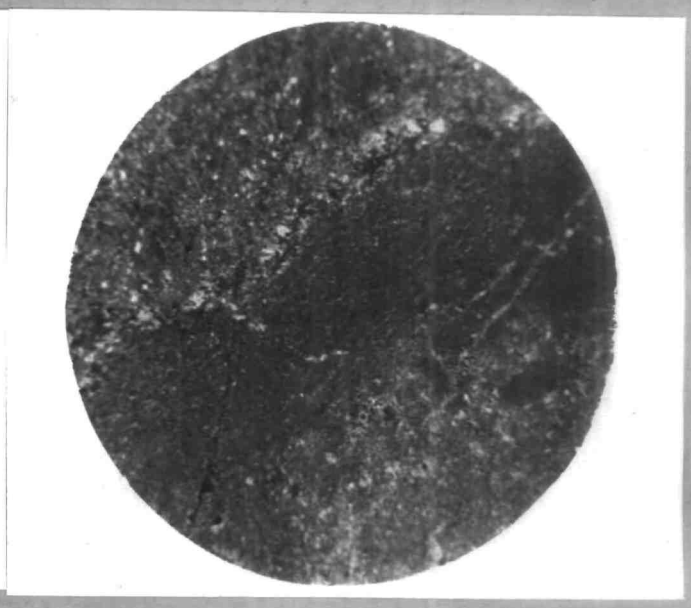

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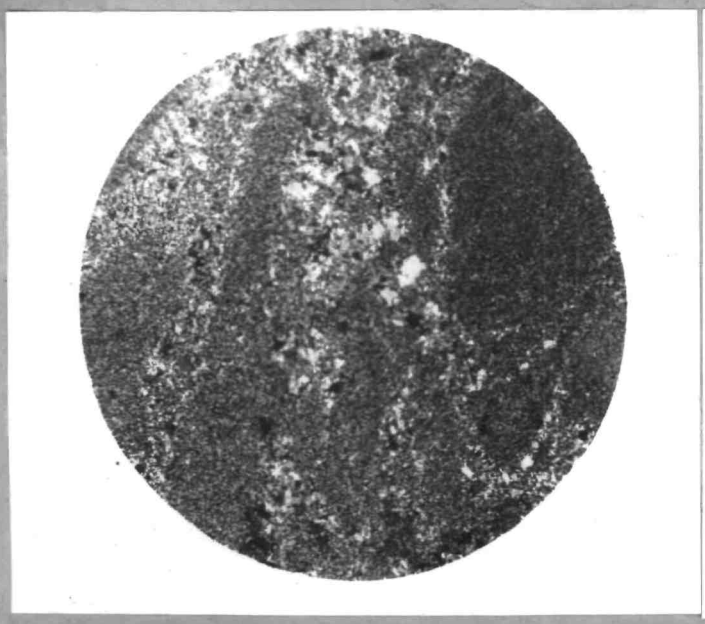

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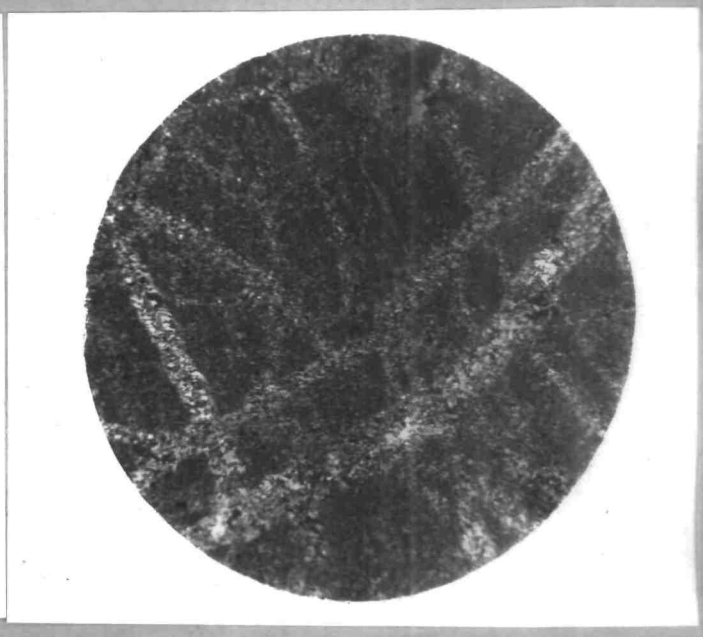

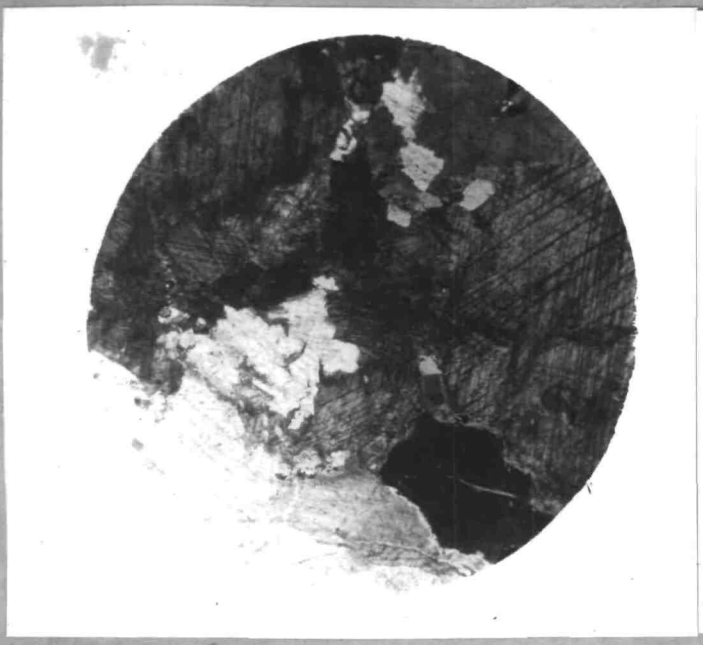

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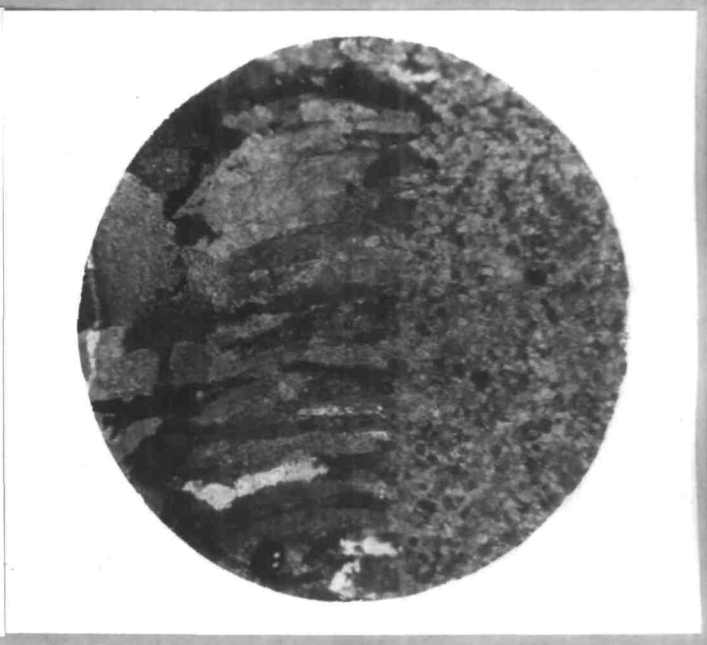

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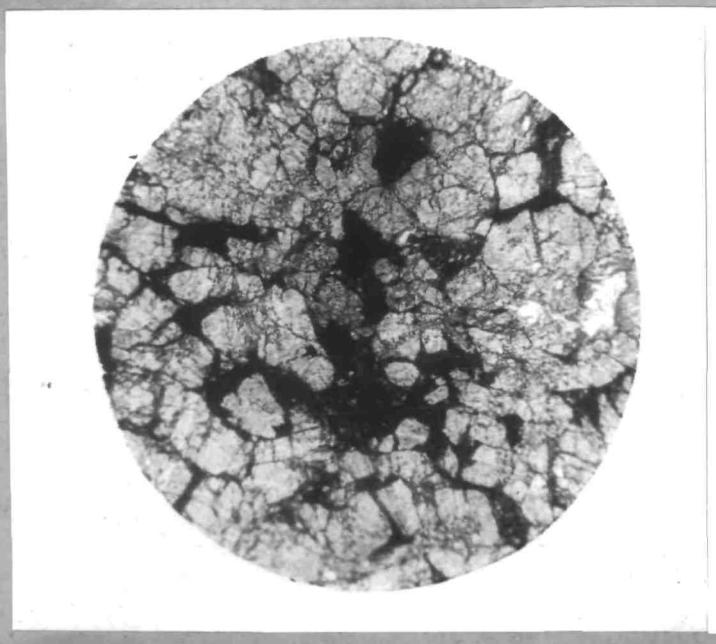

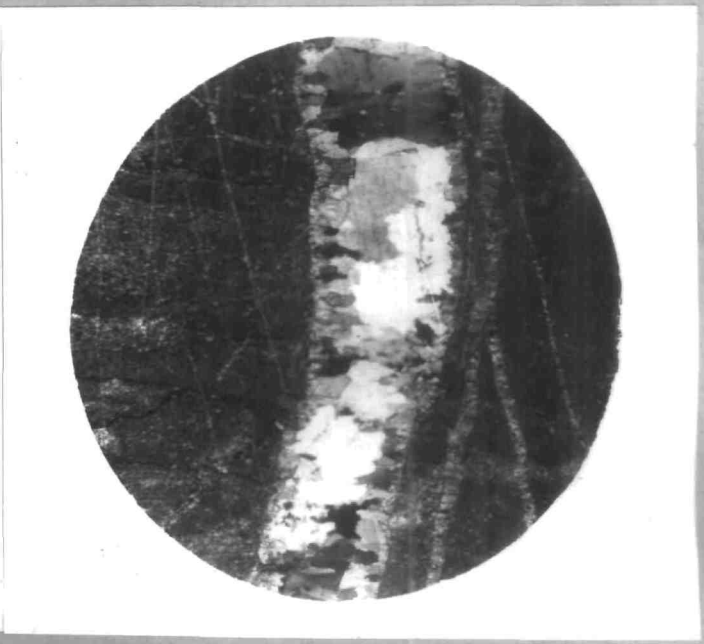

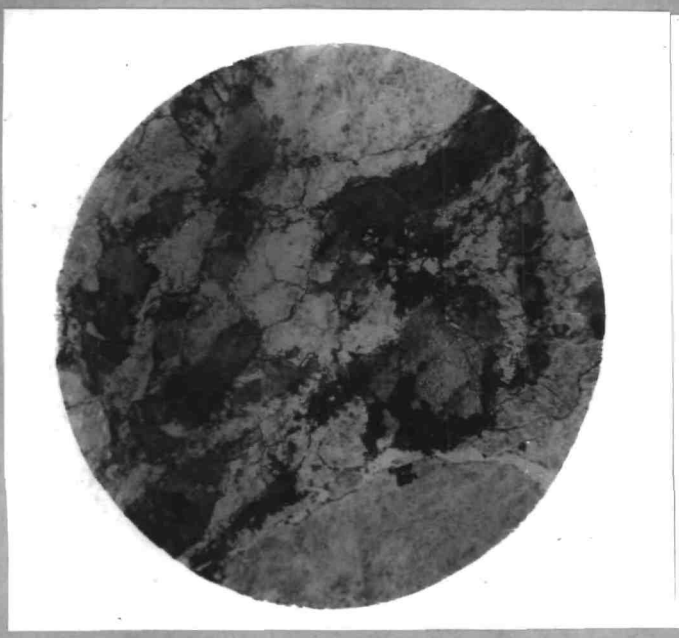

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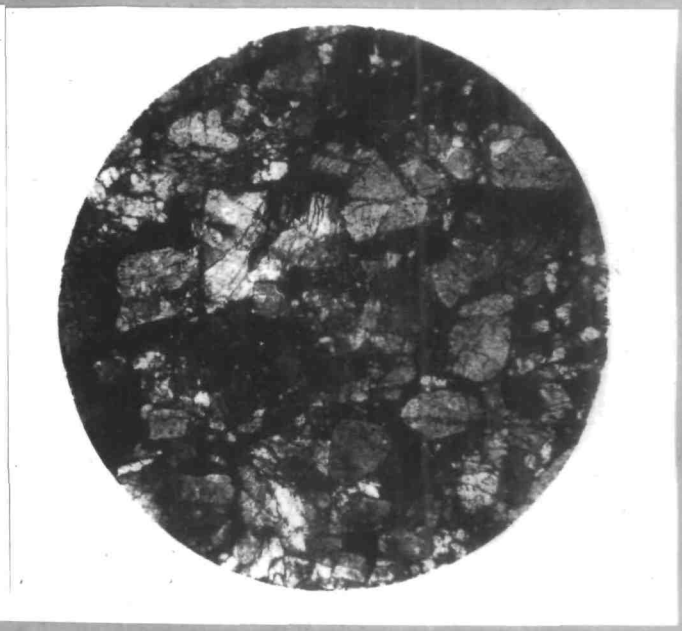

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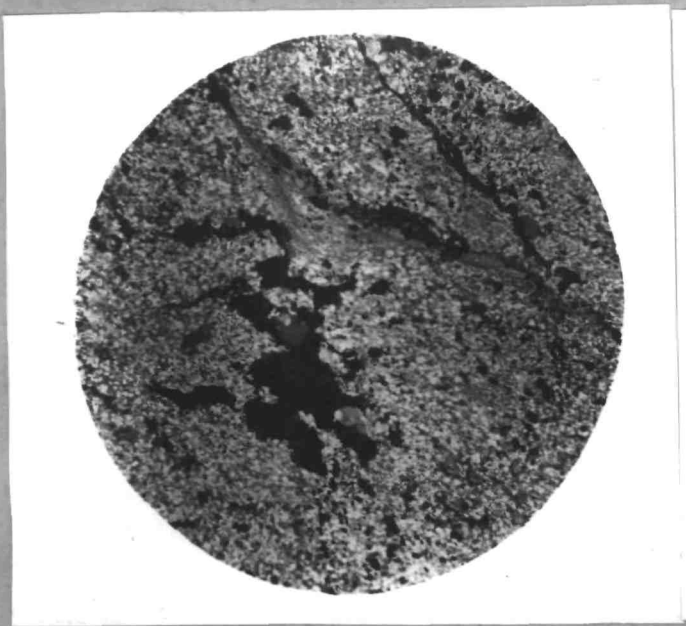

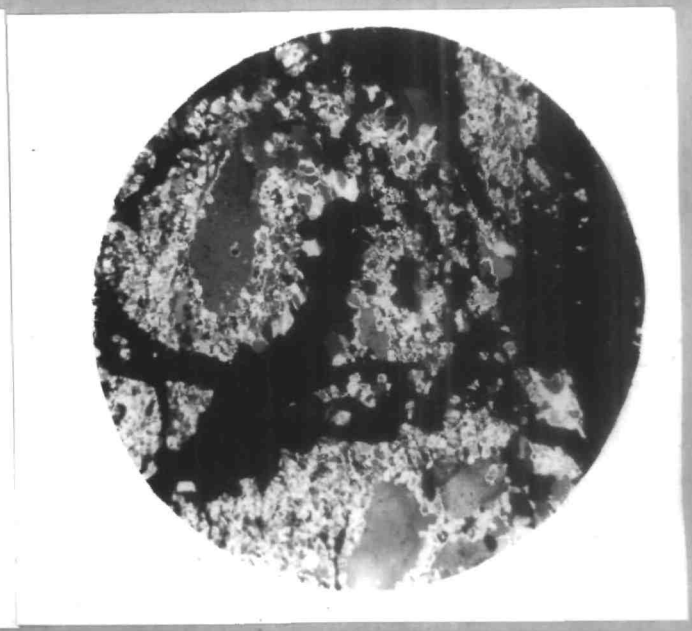

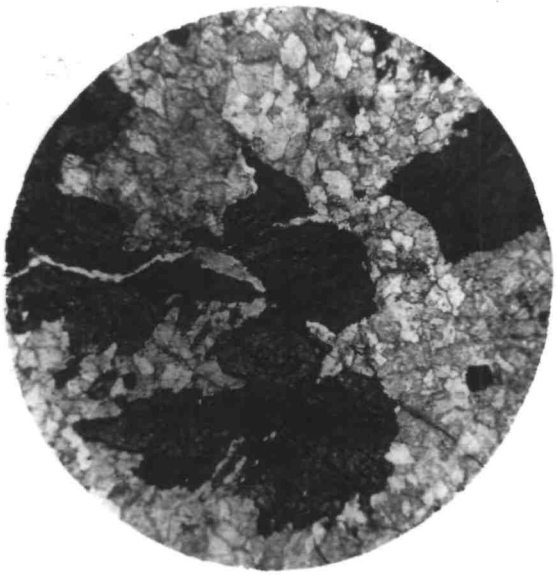

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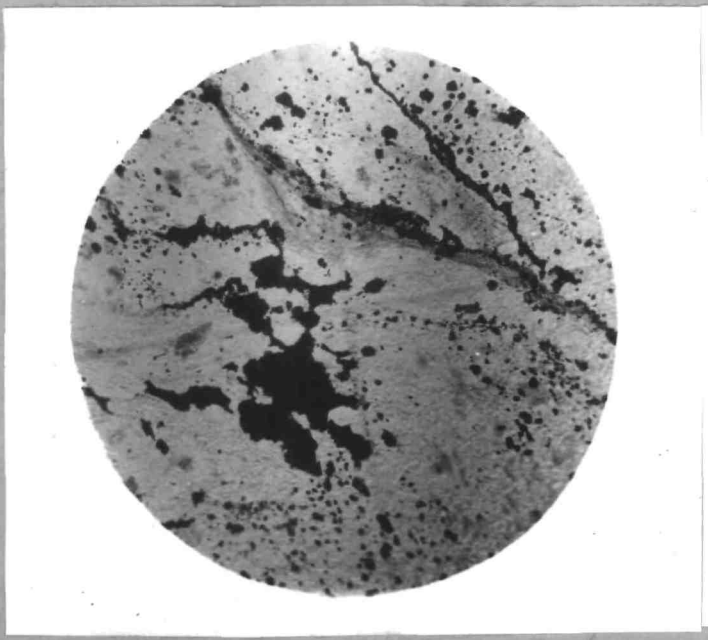

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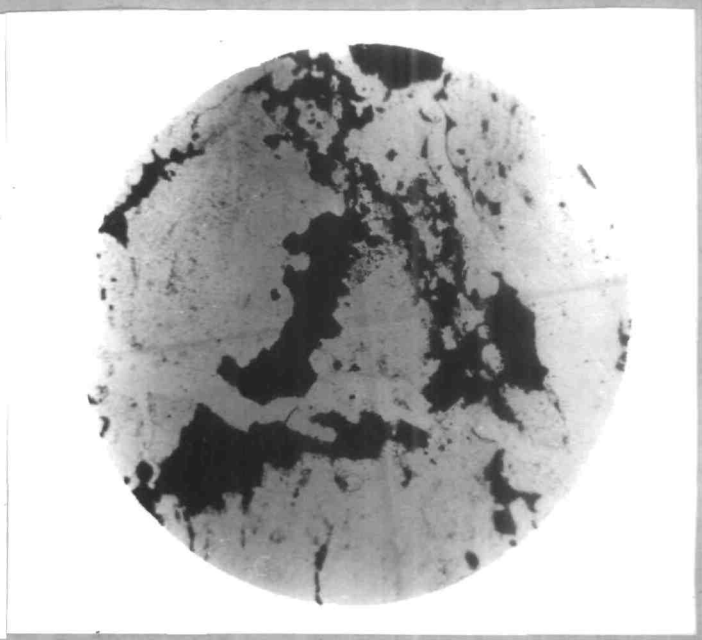

PLATE XVI

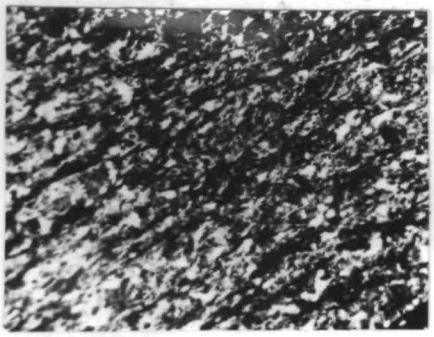

Fig. 1

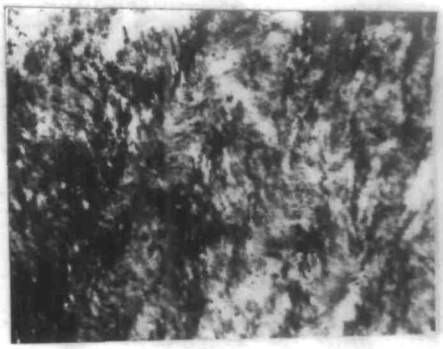

Fig. 2

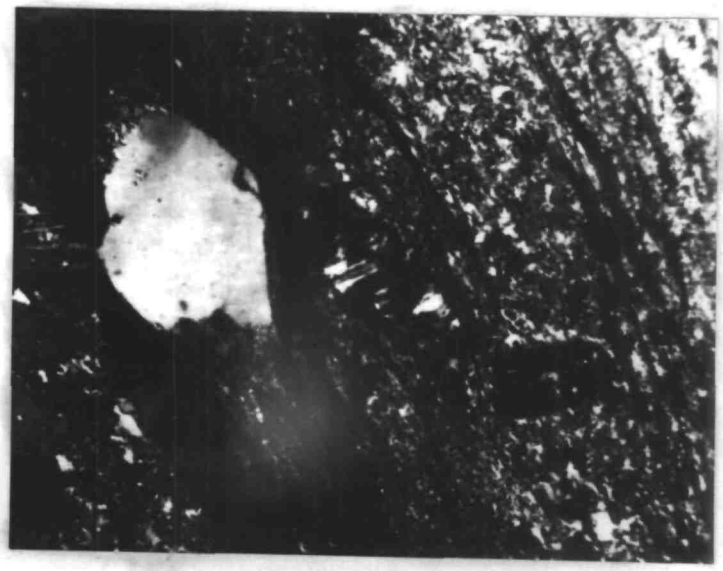

Fig. 3

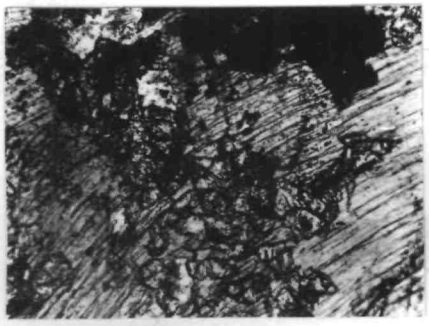

Fig. 4

Fig. 5

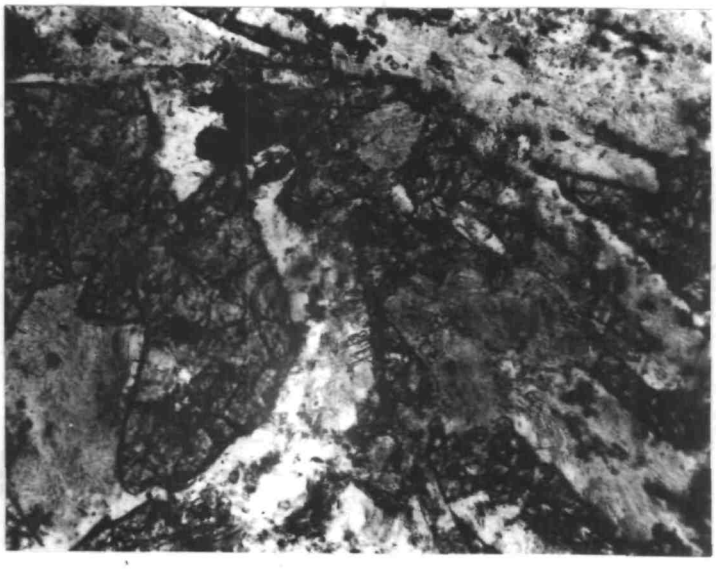

Fig.2

Fig.1

PLATE XVIII

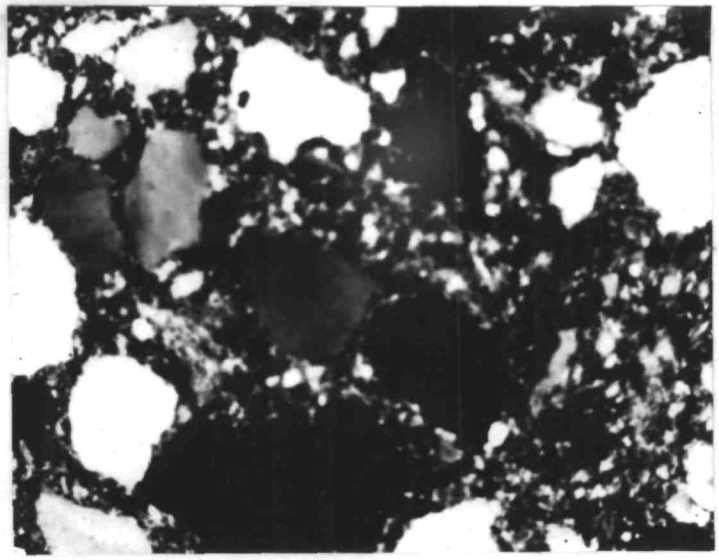

Fig.1

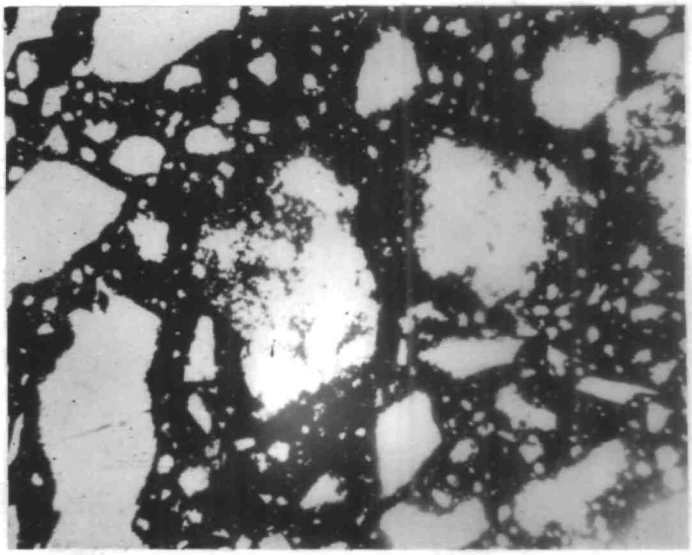

Fig. 2

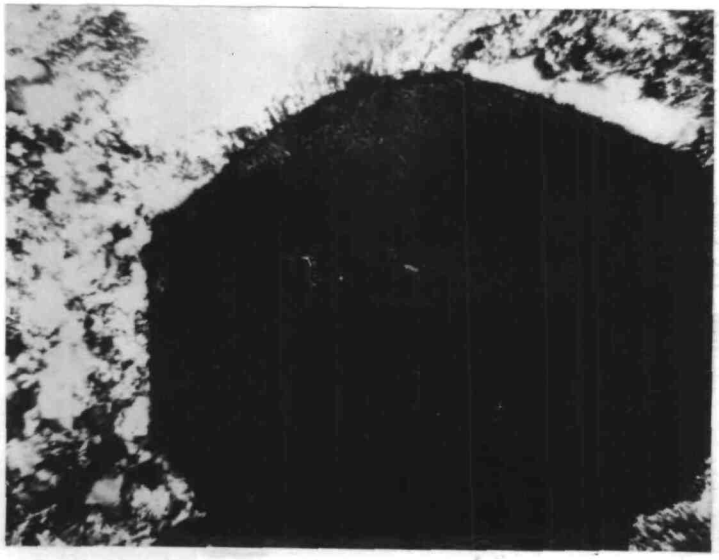

Fig. 3

PLATE XIX

Fig. 1

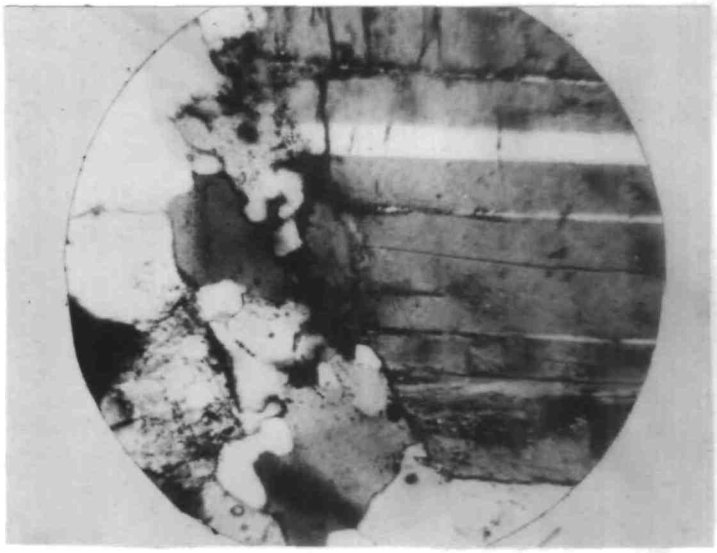

Fig. 2

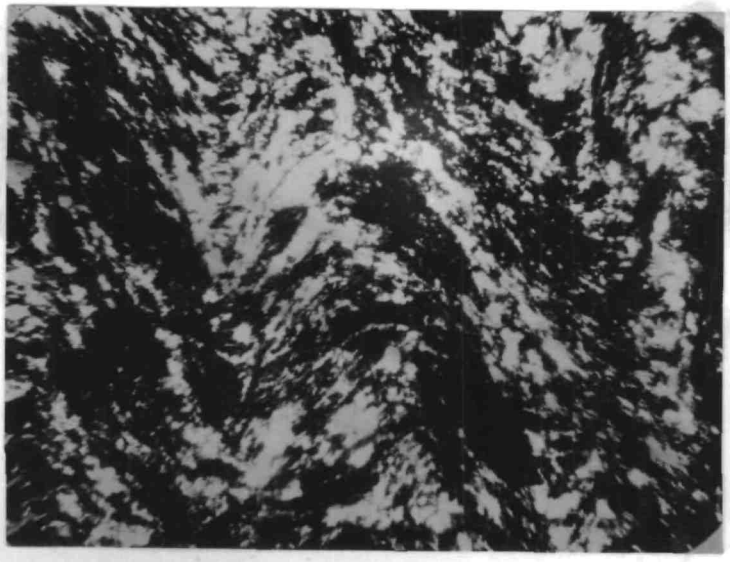

Fig. 3

PLATE XX

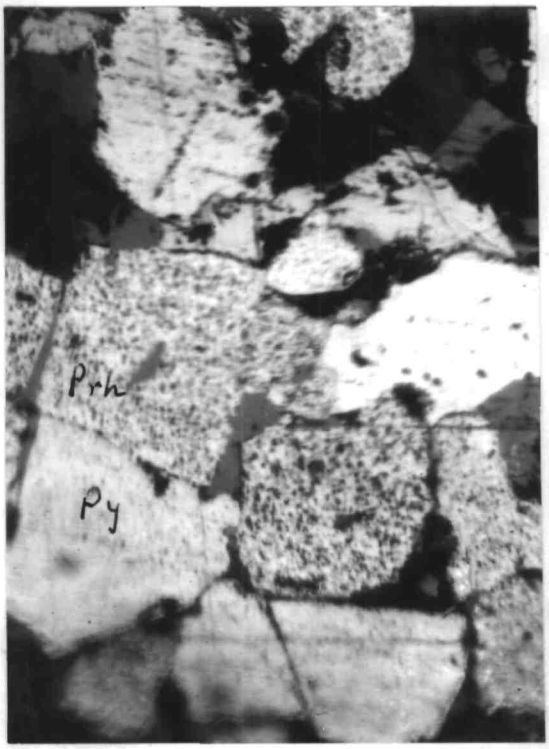

Fig. 1

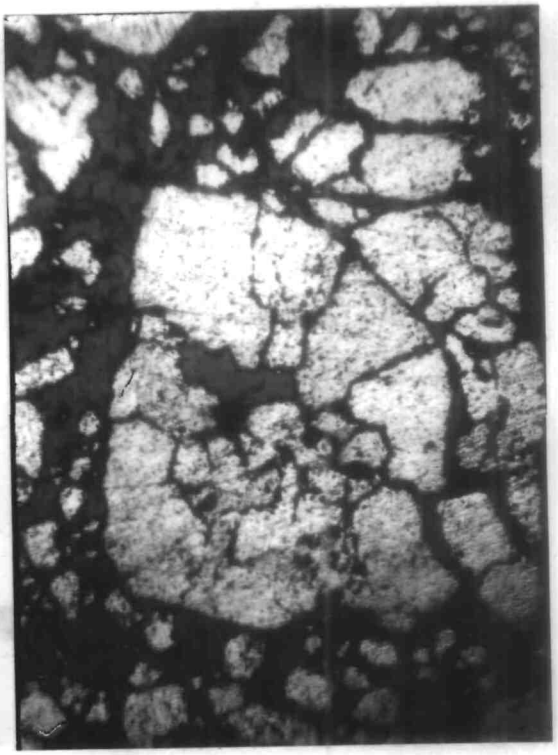

Fig. 2

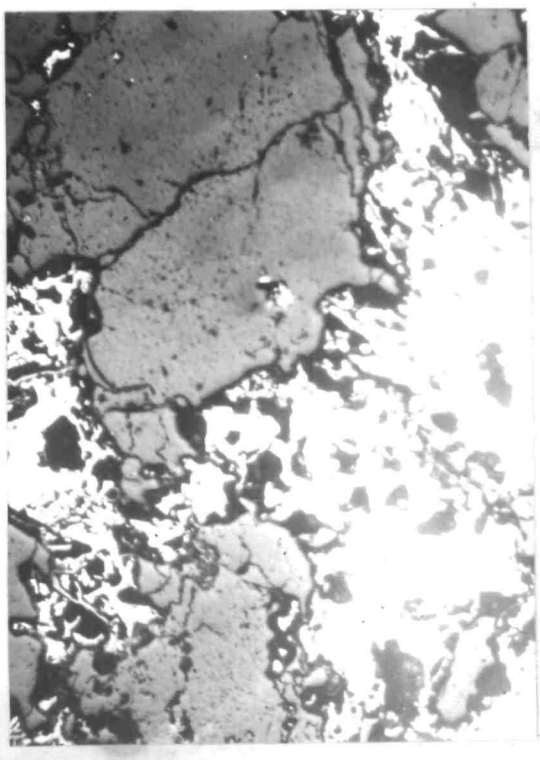

Fig. 3

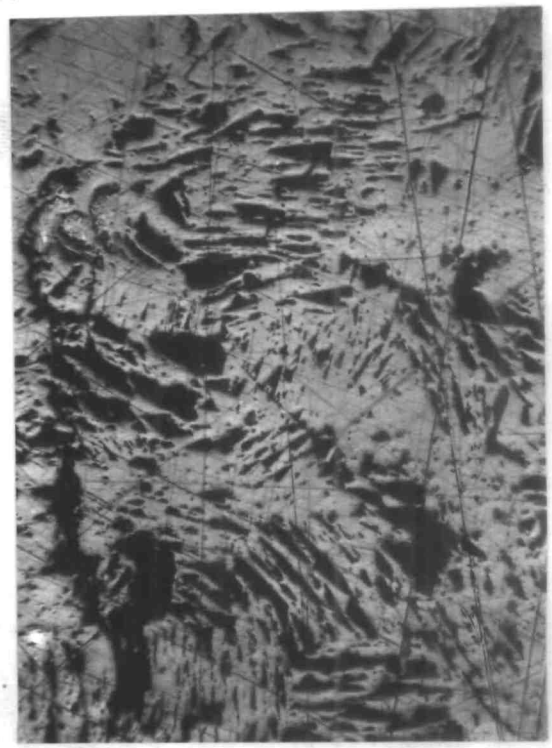

Fig. 4

PLATE XXI

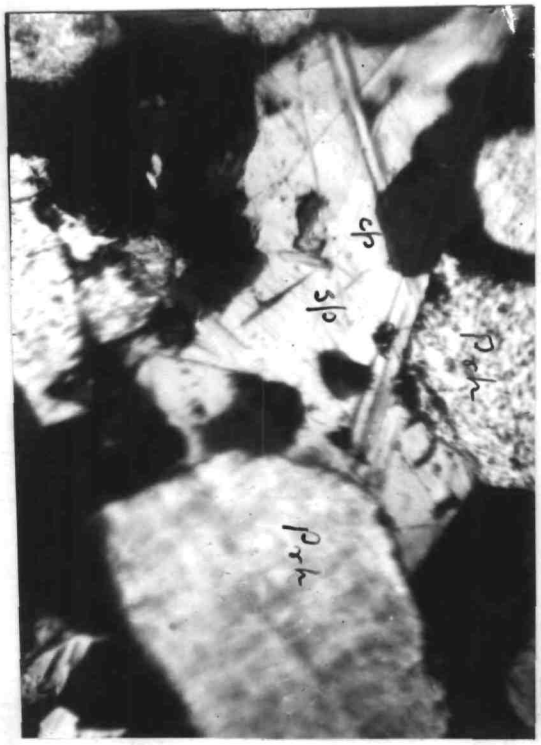

Fig.1

Fig. 2

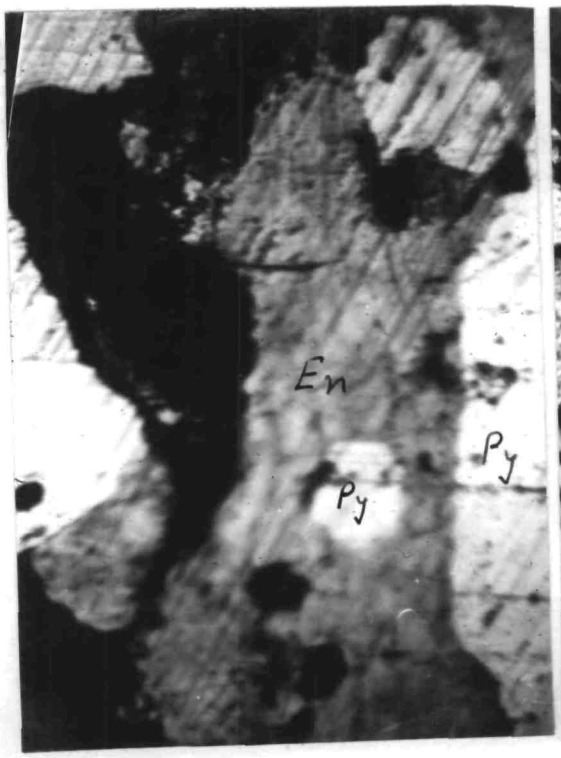

Fig. 3

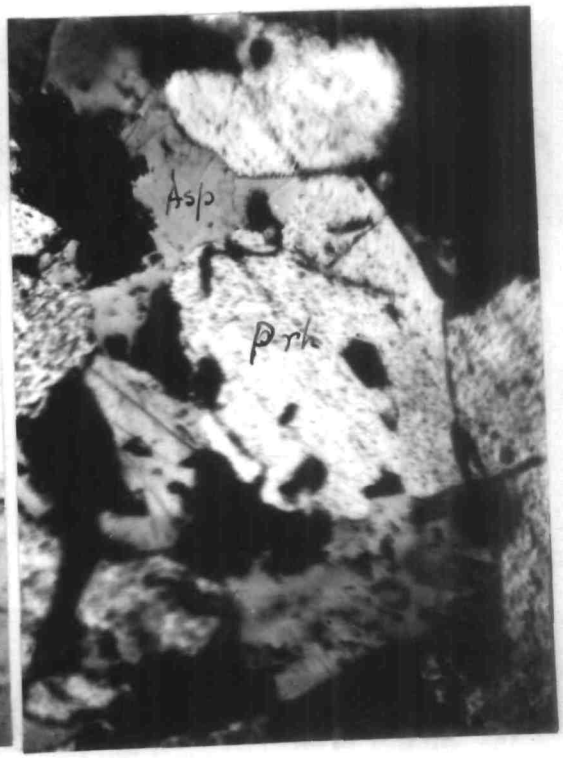

Fig. 4

APPENDIX

TABLE - 27 Minor and trace elements in limestones (unaltered) - (ppm values)

Sample No.	Mn	Mo	Ti	V	Nb	Ba	Co	Cr	Cu	Pb	Zn	Ni	Sr	Zr	La	Sc	Y	Ge	Sn	Cd	Ag	In	Sb	Ce	Th	Bi	Ga	Te	As	Si	Al
1	170	10	3000	500	400	2000	1.5	460	15	8	7.5	500	4.0	NF	NF	NF	NF	NF	NF	NF	300	NF	NF	NF	NF	NF	NF	NF	2.5	1000	3600
2	100	12	3300	650	NF	4500	30.0	900	10	2	3.	50	2.5	NF	NF	NF	NF	NF	NF	NF	100	NF	NF	NF	NF	NF	NF	NF	NF	2000	2600
3	800	15	3500	600	300	5500	10.0	200	3	4	10	600	3.0	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	1.5	2500	3600
4	500	20	4500	665	400	3500	1.0	300	7.5	NF	NF	315	4.5	NF	NF	NF	NF	NF	NF	NF	250	NF	NF	NF	NF	NF	NF	NF	2.5	3100	4500
5	600	25	3800	670	350	5500	10.0	100	15	1	NF	650	2.5	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	1.0	4000	4950
6	500	25	3900	520	300	5500	90.0	85	2	NF	6	600	2.5	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	1.8	4000	5400
7	1500	7	3300	550	260	2300	22.0	100	5	NF	4	2000	4.25	NF	NF	NF	NF	NF	NF	NF	400	NF	NF	NF	NF	NF	NF	NF	2.5	5000	5400
8	500	16	4500	640	300	3500	25.0	250	2	8.5	2	6000	4.00	NF	NF	NF	NF	NF	NF	NF	300	NF	NF	NF	NF	NF	NF	NF	2.0	>5000	5400
9	750	13	4000	600	360	3000	10.0	90	10	6.0	5	550	4.00	NF	NF	NF	NF	NF	NF	NF	400	NF	NF	NF	NF	NF	NF	NF	2.5	>5000	5700
10	1000	19	3500	570	400	5500	100.0	110	5	4.0	8	500	4.0	NF	NF	NF	NF	NF	NF	NF	1000	NF	NF	NF	NF	NF	NF	NF	NF	4500	>5000
11	3200	20	3300	550	300	150	25.0	150	8	NF	5	950	4.5	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	NF	4000	5300
12	1250	10	1200	520	260	5300	37.5	85	5	10	8.5	3500	4.0	NF	NF	NF	NF	NF	NF	NF	500	NF	NF	NF	NF	NF	NF	NF	1.25	5000	4250
13	550	25	3300	550	300	5200	100.0	450	NF	5	7.5	900	4.25	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	1.25	>5000	4600
14	500	25	3700	510	300	2200	25.0	90	2	4	3.5	550	2.5	NF	NF	NF	NF	NF	NF	NF	300	NF	NF	NF	NF	NF	NF	NF	2.5	5000	4300
15	260	13	4200	450	300	5000	1.5	3000	NF	2	2.0	2500	3.25	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	1.8	3000	4000
16	4000	15	3400	530	340	1300	50.0	200	NF	NF	9.0	5700	4.0	NF	NF	NF	NF	NF	NF	NF	100	NF	NF	NF	NF	NF	NF	NF	1.8	3500	4900
17	700	20	2000	600	400	4500	14.0	100	5	10	6.5	500	3.5	NF	NF	NF	NF	NF	NF	NF	50	NF	NF	NF	NF	NF	NF	NF	1.8	3200	4700
18	650	25	750	640	360	5700	13.0	530	NF	NF	NF	220	4.0	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	NF	3900	5300
19	100	10	750	640	320	3200	14.0	110	NF	NF	NF	170	5.0	NF	NF	NF	NF	NF	NF	NF	100	NF	NF	NF	NF	NF	NF	NF	NF	4500	5000
20	430	12	1000	660	340	4500	32.0	90	4	10	NF	300	3.0	NF	NF	NF	NF	NF	NF	NF	150	NF	NF	NF	NF	NF	NF	NF	NF	4900	4100
21	800	15	1300	680	60	2400	1.5	550	NF	15	15	400	4.5	NF	NF	NF	NF	NF	NF	NF	250	NF	NF	NF	NF	NF	NF	NF	NF	4100	4600
22	3500	25	1400	400	300	2400	10.0	300	1.5	NF	NF	400	3.25	NF	NF	NF	NF	NF	NF	NF	75	NF	NF	NF	NF	NF	NF	NF	NF	5800	5300
23	1000	20	450	700	340	1400	30.0	25	10.0	NF	NF	450	4.0	NF	NF	NF	NF	NF	NF	NF	150	NF	NF	NF	NF	NF	NF	NF	NF	5300	4900
24	650	15	4100	520	400	1500	5.0	25	NF	10	NF	350	2.5	NF	NF	NF	NF	NF	NF	NF	200	NF	NF	NF	NF	NF	NF	NF	NF	2900	4300
25	2000	15	1000	510	380	3500	14.0	550	10	5	5	900	3.5	NF	NF	NF	NF	NF	NF	NF	100	NF	NF	NF	NF	NF	NF	NF	NF	900	5500
26	650	25	1800	520	200	1500	33.0	150	NF	NF	NF	1500	4.0	NF	NF	NF	NF	NF	NF	NF	35	NF	NF	NF	NF	NF	NF	NF	NF	500	5300
27	400	12	600	700	150	1000	25.0	180	5	2	10	2500	3.5	NF	NF	NF	NF	NF	NF	NF	15	NF	NF	NF	NF	NF	NF	NF	NF	250	5000
28	500	10	2550	150	300	500	4.0	30	NF	15	5	600	2.5	NF	NF	NF	NF	NF	NF	NF	25	NF	NF	NF	NF	NF	NF	NF	NF	200	4500
29	750	8	4000	500	400	300	5.0	100	NF	NF	5	800	1.5	NF	NF	NF	NF	NF	NF	NF	50	NF	NF	NF	NF	NF	NF	NF	NF	150	5000
30	1500	6	4500	650	520	100	2.5	25	2	11.5	2	400	1.0	NF	NF	NF	NF	NF	NF	NF	30	NF	NF	NF	NF	NF	NF	NF	NF	150	5700

NF = Not found

TABLE - 28 Minor and trace elements in dolomitic limestones (altered) (ppm values)

Sample No.	Mn	Mo	Ti	V	Nb	Ba	Co	Cr	Cu	Pb	Zn	Ni	Sr	Zr	La	Sc	Y	Ge	Sn	Cd	Ag	In	Sb	Ce	Th	Bi	Ga	Ta	As	Si	Al
1	200	50	40	50	20	3000	5	NF	5	3000	10000	30	350	5.0	37.5	5	5	30	10	25	50	10	20	28	29	5	20	6.25	12.5	1000	8000
2	200	100	100	30	50	NF	10	500	10	500	5000	150	200	11.5	42	2	10	7.5	20	35	40	5	4	24	10	11	15	NF	6	2000	> 5000
3	250	200	380	5	75	3000	NF	2000	12.5	10000	7500	50	75	2.5	NF	3.5	3	3	17	40	NF	9	9	20	19.5	NF	12	12.5	6	2300	5500
4	4000	300	1000	10	200	NF	NF	3500	7.5	5000	5000	20	50	3.5	NF	5	NF	NF	15	10	40	5	12	15	26.5	20	8	5	7	4000	5000
5	3000	25	2000	470	390	100	NF	600	5	1000	3000	50	50	1.5	12.5	7	19	NF	13	35	NF	10	3.5	10	10	8	5	25	27.5	3400	4500
6	2000	40	50	100	15	300	17	1500	15	10000	500	200	100	11.5	25	10	17	7.5	15	20	25	7.5	5	NF	5	3	NF	37.5	50	4500	360
7	1000	50	40	27	50	1000	15	NF	6.5	3000	1000	3000	150	20	37.5	12	14	3	5	500	15	7	8	5	NF	5	NF	20	82.5	5000	4350
8	4000	60	1000	410	250	3000	NF	300	20	7500	500	56	200	30	25	15	9	7.5	10	200	20	2.5	3	5	10	2	5	67.5	300	5000	4600
9	3000	50	4000	40	NF	NF	NF	NF	10	5000	3000	150	250	30	12.5	10	5	3	15	100	25	5	5	NF	18	7	NF	65	420	3900	4600
10	3000	100	3800	310	150	50	5	400	125	10000	750	200	300	40	25	18	3	3	NF	350	40	9	8	3	20	5	3	100	750	3400	4600
11	1000	150	2000	40	NF	20	13	NF	20	7500	500	5000	15	5	30	20	7	NF	NF	450	NF	10	11	2	15	NF	NF	95	1000	4400	5300
12	3000	45	100	45	100	300	7.5	NF	17.5	5000	10000	400	10	2.5	NF	3	2	7.5	NF	9000	40	NF	NF	NF	27	17	2	77.5	2000	2000	4900
13	4000	50	500	50	50	500	2.5	2900	30	10000	5000	150	7	5	NF	5	NF	4.5	14	9500	NF	1.5	14	NF	20	NF	6	87.5	1600	3000	5100
14	3500	100	1000	40	20	1000	10	NF	16	5000	500	20	NF	11.5	20	7	1.5	3.0	10	5000	NF	NF	9	5	15	5	10	50	2000	4200	5900
15	1000	150	2000	25	40	200	5	1500	10	7500	3000	200	75	5	25	5	NF	7.5	18	7500	35	NF	2	3	11	NF	4	NF	650	3400	6000
16	2000	200	3000	30	75	750	6	200	11.5	3000	10000	300	NF	2.5	37.5	3	10	15	15	5000	20	10	19.5	7	6	10	2	17.5	50	1200	5700
17	4000	300	1000	35	35	3000	1.5	300	40.0	4000	300	400	NF	1.0	25	NF	5	12	15	500	40	7.5	12.0	10	4	3	2	NF	1350	3000	5500
18	3000	75	2000	200	90	2000	9	NF	15	3000	4000	3000	20	25	45	5	3	7.5	NF	400	25	5	5	5	2	7	NF	NF	85	4200	5300
19	4000	150	3000	20	NF	300	NF	1500	5	1000	7850	500	10	NF	325	2	5	10	NF	25	25	7.5	3	7	5	15	3	12.5	45	4800	4600
20	3000	60	1500	100	100	1000	NF	2000	13	500	7500	400	25	NF	25	NF	3	13	NF	50	NF	9	19	NF	20	NF	2	NF	35	3500	4200
21	4000	75	2000	10	75	400	10	2700	20	300	> 10000	300	15	NF	37.5	NF	5	18	7	300	10	10	NF	10	NF	6	5	17.5	25	4450	5000
22	3000	200	500	15	25	300	5	2500	7.5	100	500	350	10	11.5	22	NF	10	22.5	5	400	15	7.5	8.5	NF	2	NF	NF	55	50	4000	> 5000
23	2000	100	1000	20	150	NF	12	NF	15	50	3000	200	NF	25	5	NF	5	27	3	> 5000	20	5	NF	7	3.5	16	NF	83	250	3400	5500
24	4000	45	500	35	25	NF	7.5	2000	10	50	> 5000	100	NF	1.5	10	5	2	30	10	4500	25	9	14	5	10	NF	9	100	1450	1000	5000
25	2500	45	75	50	50	NF	NF	1000	40	50	3000	20	15	2.5	20	3	3	7.5	NF	5500	35	10	10	NF	13	10	NF	95	1000	700	4700
26	4000	50	100	120	25	NF	10	500	34	30	500	200	50	1.5	4	2	NF	3.0	NF	> 5000	15	NF	NF	3	23	3	3	75	50	300	5500
27	2000	70	2000	210	40	NF	NF	2500	20	100	100	100	25	5.0	NF	NF	4	4.5	13	5000	NF	NF	13	5	NF	NF	NF	37.5	42.5	150	5000
28	3000	85	1000	13	25	NF	2.5	2800	17.5	500	500	50	50	3.5	32	NF	NF	3.0	10	8000	NF	6.5	10	10	9	5	8.5	5.0	5.0	100	> 5000
29	2500	90	100	10	35	100	5.0	2000	15.0	150	100	100	135	NF	NF	NF	NF	4.5	NF	6000	25	7.5	NF	NF	14	10	NF	10	7.5	450	7500
30	2000	50	500	13	75	300	25	41	11.0	50	50	150	25	25	20	5	5	7.5	5	9500	NF	9.0	5.5	20	30	20	5	12.5	12.5	950	> 5000

TABLE - 20 Minor and trace elements in slates (altered) (ppm values)

Sample No.	Zn	As	Ta	Cu	Th	Y	Sr	La	Ga	Ge	Ce	Bi	Be	Ag	Al	Cr	Sr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti	Zr
1	300	850	50	> 10000	3000	6000	500	26	43	17	450	50	5.0	2	2100	3900	100	6	100	10	5	10	5	3000	5800	48
2	300	500	100	3200	6000	5000	200	20	25	5	350	380	5.0	2	3800	3250	150	5	50	100	15	5	NF	2000	5000	43
3	100	750	300	5000	4000	4500	390	23	40	16	410	510	5.0	3	4400	2700	200	NF	75	500	10	NF	NF	1500	4000	40
4	50	340	75	4500	3500	4000	100	19	35	12	290	380	2.5	4	5100	2400	250	NF	37	75	18	NF	NF	500	2000	20
5	75	925	400	> 5000	3000	3000	50	19	32	10	230	260	NF	2	5500	3000	200	NF	12	87	NF	7	7.5	300	4500	10
6	300	750	50	5500	4000	4000	150	NF	15	7	300	50	2.5	5	> 5000	1500	150	NF	7	300	4	5	10	1000	3200	45
7	300	500	NF	> 1000	3000	500	290	NF	25	10	50	NF	1.0	10	7000	850	300	5	13	75	6	NF	13	2600	3900	40
8	100	750	NF	7500	2000	3000	360	NF	37	8	25	NF	2.5	20	8000	650	350	8	25	500	NF	NF	NF	1500	5600	25
9	260	300	75	5000	3700	4000	100	NF	NF	5	5	25	50	3.5	25	> 10000	350	300	5	32	1000	NF	7	NF	2000	5000	35
10	500	500	300	> 5000	5000	3500	750	10	40	8	85	225	4.5	30	5900	750	400	NF	75	63	10	3	7.5	2500	3000	45
11	100	100	75	5000	5000	4000	300	12	12	NF	380	500	1.5	35	6000	1200	370	NF	50	87	NF	14	10	750	4000	42
12	50	750	NF	5000	1000	3000	300	14	40	11	100	NF	2.5	30	5900	1500	400	NF	37	100	4	10	5	1000	2900	45
13	100	500	50	4500	4000	4000	140	10	NF	7	50	100	4.0	25	8000	950	260	5	37	500	7	6	NF	2000	2000	42
14	85	380	NF	4800	3000	3000	230	13	13	5	70	220	3.5	13	5500	600	300	8	25	750	4	NF	6.5	3500	2500	10
15	65	220	35	5500	4500	5000	50	7	18	10	50	70	NF	15	7000	2000	150	5	33	100	NF	NF	7.5	1500	1700	30
16	100	750	60	5000	3000	4000	70	12	32	5	80	340	1.5	20	4800	2200	200	NF	18	300	NF	7	11	1000	3500	40
17	420	100	85	5800	4000	4500	180	NF	15	NF	NF	50	3.0	25	4000	1000	260	NF	25	850	5	NF	NF	750	4000	48
18	55	750	NF	500	3100	500	210	25	38	5	50	NF	NF	10	2400	1600	100	5	18	50	NF	NF	NF	2000	4500	5
19	77	75	NF	1000	4000	3000	240	16	25	10	25	100	2.0	15	5500	3000	150	4	10	75	10	7	NF	3900	5500	15
20	100	300	50	500	4700	500	400	11	20	15	75	380	NF	5	5000	3600	200	7	25	625	6	5	5	2750	5000	10

NF = Not found

TABLE - 30 Minor and trace elements in slates (unaltered) (ppm values)

Sample No.	Zn	As	Te	Cu	Th	Y	Sl	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Sr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti	Zr
1	25	75	90	100	NF	NF	20	5	12	4	25	NF	NF	50	3900	500	50	1500	450	9	NF	185	2900	1500	2000	12
2	50	50	75	50	NF	NF	NF	NF	NF	NF	NF	NF	NF	25	3500	100	30	2000	260	10	NF	100	2500	1000	750	NF
3	75	650	50	100	NF	30	NF	NF	NF	NF	10	1.5	NF	100	3000	100	70	100	100	NF	NF	160	1000	1500	1000	25
4	NF	NF	75	30	NF	NF	NF	NF	NF	NF	NF	NF	NF	200	3400	500	NF	1000	200	NF	NF	200	1600	2000	1500	NF
5	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	75	NF	NF	200	2500	325	NF	75	75	3	3	50	2100	100	1000	20
6	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	125	1400	150	30	1200	87	NF	NF	30	2300	50	1500	16
7	25	NF	NF	NF	NF	NF	NF	NF	NF	5	NF	1.0	NF	160	800	100	NF	1800	75	3	NF	100	2700	30	1000	12
8	NF	NF	NF	70	NF	NF	NF	NF	NF	NF	20	NF	NF	190	1500	150	60	300	380	NF	NF	150	2900	80	1300	NF
9	NF	15	20	30	NF	20	NF	NF	NF	NF	NF	NF	NF	100	1900	250	NF	100	380	NF	2	180	1900	1500	1500	NF
10	NF	NF	NF	NF	30	NF	35	10	6	NF	75	NF	NF	17	2800	250	NF	90	75	NF	NF	120	2500	100	1000	33
11	NF	NF	NF	20	NF	NF	NF	NF	NF	NF	NF	NF	NF	37	3500	350	20	1000	90	3	NF	60	2800	750	100	NF
12	35	NF	NF	30	NF	NF	NF	NF	NF	NF	NF	NF	NF	100	1900	150	NF	2000	30	NF	NF	190	1500	1000	300	NF
13	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	160	1000	100	30	500	20	NF	NF	120	2400	500	50	33
14	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	30	NF	NF	200	500	400	NF	800	50	NF	NF	170	900	1000	100	NF
15	NF	NF	50	50	NF	NF	NF	NF	NF	NF	NF	NF	NF	140	1800	200	NF	1500	100	NF	NF	140	1900	750	300	NF
16	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	190	2700	400	NF	50	67	3	NF	90	2300	750	60	16
17	35	NF	NF	NF	NF	NF	NF	NF	NF	NF	10	NF	NF	37	2700	450	NF	75	50	NF	NF	50	500	500	100	NF
18	NF	NF	NF	25	NF	NF	NF	5	NF	NF	NF	NF	NF	210	2700	250	30	50	35	NF	NF	170	800	100	300	8
19	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	260	3400	150	NF	100	380	NF	NF	120	600	300	100	NF
20	30	50	25	100	20	20	20	3	12	7	25	2	NF	240	3900	150	20	500	100	4	3	90	1400	100	500	20

NF = Not found

TABLE - 31 Minor and trace elements in phyllites (Altered) (ppm values)

Sample No.	Zn	As	Te	Cu	Th	Y	Sc	La	Ce	Ga	Ce	Bi	Be	Ag	Al	Cr	Sr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti	Zr
1	3400	1500	300	> 10000	2000	3000	2000	20	15	10	600	500	5	8	5000	350	150	5	180	3000	18	8	9	4000	2000	12.5
2	3000	2000	500	> 5000	4000	6000	3000	29	50	18	400	100	2	10	7500	500	230	8	7	2100	17	5	5	3000	3500	35.5
3	2600	2000	300	> 6600	5100	5200	2000	25	37	14	600	500	3.5	8	8000	750	150	6	12	2600	14	NF	8	3500	2600	15.0
4	5000	2000	500	> 10000	6000	4000	500	20	50	10	500	300	4	10	5900	850	60	3	78	1600	18	NF	9.5	3000	3700	NF
5	3000	1000	300	> 6200	5100	5900	1000	29	37	14	450	80	5	13	7500	900	350	NF	100	2800	10	NF	3	3600	2500	35
6	500	1000	500	> 9600	6000	5000	3000	25	48	19	420	460	5	13	8000	1000	300	NF	62	500	18	2	4	2000	4000	25
7	950	100	100	7000	4100	6000	1000	20	40	16	500	50	3.5	10	9000	1600	200	NF	40	2000	20	NF	4	3000	3300	12.5
8	750	50	50	1000	5000	100	2000	20	50	5	450	3000	NF	8	7500	2200	250	5	76	2700	19	NF	NF	2000	2600	20
9	500	25	35	100	1000	60	2900	10	37	14	200	75	3	21	> 5000	2700	310	NF	12	1500	5	3	NF	2600	2000	7
10	750	50	15	3900	1000	380	1000	15	20	16	350	380	2	27	5000	3000	400	NF	25	1000	8	NF	NF	3000	3500	NF
11	1400	75	NF	3500	2100	100	2350	11	30	10	200	100	1	30	5500	3500	250	NF	7	2000	13	NF	2.5	1000	3000	7
12	1800	260	25	4900	3000	500	3000	16	40	14	100	75	1	35	3600	3900	100	3	5	50	13	NF	NF	2000	2000	NF
13	850	55	NF	3300	500	750	2500	15	40	12	100	75	1.5	40	2100	3700	300	NF	15	75	12	NF	NF	1000	3700	7
14	750	15	35	> 5000	100	65	1000	NF	13	NF	40	NF	1.5	39	3900	1300	360	NF	10	300	18	NF	NF	500	3900	NF
15	5000	500	NF	7500	2000	1000	2000	6	NF	6	200	60	NF	20	5100	850	200	NF	150	1000	14	3	NF	100	2900	20
16	2600	80	NF	8000	3900	3500	50	10	12	NF	150	300	2.5	25	5500	2700	250	5	15	1700	5	NF	2	2500	2500	10
17	550	180	25	> 10000	4500	30	170	15	NF	7	NF	NF	3.5	30	> 5000	2500	200	NF	190	2200	19	NF	NF	1900	3000	NF
18	750	80	15	> 5000	5200	70	220	10	25	15	540	300	5	14	7000	3500	300	NF	100	2500	15	NF	NF	950	900	15
19	500	55	10	5500	300	100	240	25	50	24	460	100	5	21	7500	1500	320	NF	150	1500	19	NF	NF	3500	1000	7
20	3000	80	NF	8000	1000	500	90	NF	NF	9	300	75	3	13	9000	2900	250	5	20	1000	14	3	3.5	3000	2000	12.5

NF = Not found

TABLE - 32 Minor and trace elements in phyllites (unaltered) (ppm values)

Sample No.	Zn	As	Ta	Cu	Th	Y	Sc	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Sr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti	Zr
1	35	60	NF	50	20	20	25	5	12.5	NF	200	NF	NF	20	2000	400	50	1500	1000	7	NF	500	1000	500	750	300
2	NF	NF	20	NF	NF	NF	NF	NF	NF	NF	50	NF	NF	30	1400	400	80	725	300	5	NF	300	500	100	500	100
3	15	NF	NF	NF	NF	NF	NF	10	7.5	5	80	NF	NF	40	2100	500	100	2950	500	NF	NF	100	750	300	300	200
4	NF	NF	18	20	NF	NF	NF	NF	NF	NF	NF	NF	NF	50	2500	500	80	2700	100	NF	NF	50	950	340	380	270
5	NF	NF	NF	NF	NF	NF	NF	10	NF	NF	NF	NF	NF	110	2900	350	NF	2200	45	7	3	100	750	950	60	200
6	15	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	150	3350	450	NF	2000	950	NF	NF	70	300	300	300	350
7	NF	NF	NF	NF	NF	NF	NF	NF	7.5	NF	NF	NF	NF	160	3700	250	50	2750	340	NF	NF	50	700	100	220	200
8	NF	NF	NF	35	NF	NF	NF	NF	NF	NF	NF	NF	NF	200	3900	150	30	2500	750	4	NF	70	550	300	900	100
9	NF	NF	NF	NF	30	30	20	7	NF	NF	NF	NF	NF	200	3900	450	NF	1600	850	NF	NF	100	700	70	500	290
10	NF	15	15	100	NF	NF	NF	NF	NF	12	50	NF	NF	160	3000	150	NF	2800	950	NF	NF	150	60	750	750	360
11	20	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	130	3550	300	60	2500	100	8	NF	300	100	1000	420	210
12	NF	NF	NF	30	NF	NF	NF	NF	12.5	NF	NF	NF	NF	100	3900	500	NF	2000	850	NF	NF	380	260	500	300	385
13	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	80	2400	500	NF	1500	750	NF	NF	380	500	100	80	250
14	NF	NF	NF	NF	NF	20	20	NF	NF	NF	NF	NF	NF	170	3000	500	65	1000	140	5	NF	140	825	300	40	320
15	NF	NF	NF	NF	NF	NF	NF	15	NF	NF	50	NF	NF	190	3400	400	NF	50	500	NF	NF	500	500	80	40	200
16	NF	NF	NF	20	NF	NF	NF	NF	NF	NF	NF	NF	NF	150	3800	500	30	750	900	NF	NF	420	700	300	80	370
17	NF	10	15	NF	NF	NF	NF	NF	NF	3	NF	NF	NF	120	2800	450	NF	2000	550	NF	NF	300	400	100	100	45
18	NF	NF	NF	20	NF	NF	NF	NF	NF	3	NF	NF	NF	85	3300	450	50	2600	500	NF	NF	180	950	500	30	200
19	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	80	3600	500	NF	2950	50	NF	NF	500	460	300	300	360
20	10	15	10	20	20	20	20	5	20	4	25	NF	NF	150	3900	500	100	500	420	3	3	420	750	60	75	290

NF = Not found

TABLE - 33 Minor and trace elements in schists (altered) (ppm values).

Sample No.	Zr	Zn	As	Te	Cu	Th	Y	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti
1	25.0	900	50	380	1000	3500	4700	38	47.5	15.0	300	25	5.0	40	8000	4000	42.5	170	3500	25	17	10	500	4000
2	31.25	650	2000	260	4000	3000	2000	30	25.0	18.0	400	40	2.0	35	7000	2000	47.5	47.5	3000	50	7.5	15	3000	5000
3	38.0	750	2500	160	5000	3500	3000	37	50.0	9.5	500	NF	1.5	26	> 5000	2500	12.5	100	3000	75	4.0	25	4800	6000
4	44.5	500	1500	95	> 5000	3000	4000	33	43.0	13.0	550	NF	2.5	22	5500	3000	25.0	50	2800	100	10.0	19	4000	7000
5	48.0	650	900	290	> 1000	2500	4900	30	20.0	20.0	580	365	3.5	15	> 5000	4000	37.5	12.5	2000	90	3.0	11.5	4500	8400
6	29.0	875	2000	450	>10000	2000	4700	20	33	NF	570	NF	2.5	12	7500	3500	47.0	85	2500	63	7	15	4000	9000
7	38	1000	2000	340	>10000	2700	4000	36	25	10	500	25	1.5	10	>10000	3000	100	37.5	1500	40	13	16.5	4500	8000
8	44.5	460	2000	380	5500	3400	4500	35	37.5	NF	580	NF	2.5	15	> 5000	3500	75	45	500	60	9	8.5	3000	10000
9	38	650	3000	260	5900	3700	3500	38	45	NF	550	50	1.5	13	7500	1000	45	50	100	75	12	16.5	3500	9000
10	31.25	100	2500	180	7000	3000	4000	34	37.5	10	550	500	1.5	15	8000	1500	37.5	65	50	50	8	13.5	3000	8400
11	17.5	300	1500	50	4400	1000	4500	29	25	NF	250	275	1.5	12	> 5000	2500	25	85	300	60	NF	NF	3500	8000
12	10	750	2600	25	3500	100	3800	36	45	15	100	25	2.5	14.5	7000	3000	10	170	1000	90	NF	NF	3000	8500
13	7	900	2350	90	5000	3000	4200	22	40	NF	500	NF	2	16	7500	1500	25	31	2000	70	NF	1.8	3800	8500
14	26.5	700	2900	225	4300	3600	2000	15	NF	5	200	250	2	23	5100	1200	NF	180	2500	85	3.5	5	3000	8000
15	37.0	350	2600	80	5800	3000	3000	NF	NF	NF	200	275	1.5	15	> 5000	2000	NF	150	1500	75	NF	7.5	4500	7000
16	17.5	100	1400	225	8000	2800	3500	NF	23	3.5	300	NF	2.0	20	5500	2500	NF	12.5	100	65	NF	NF	1000	10000
17	21.5	800	2000	380	7000	1700	4200	11	NF	NF	400	275	1.5	18	5000	3000	7.5	25	2000	75	6	14	100	6000
18	29	900	2600	NF	5000	2500	2500	25	12.5	5	515	NF	2	24	4000	3500	NF	17.5	900	50	NF	NF	2000	3000
19	25	950	3000	NF	2000	200	750	33	NF	NF	515	275	1.5	30	> 5000	3000	NF	45	1500	85	NF	5	3000	2000
20	21.5	80	100	25	625	1500	2000	36	25	10	510	400	1.5	33	5500	1000	12.5	25	500	45	3.5	11.5	4000	4000

NF = Not found

TABLE - 34: Minor and trace elements in schists (unaltered) (ppm values)

Sample No.	Zr	Zn	As	Ta	Cu	Th	Y	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti
1	12.5	50	400	90	87	12.5	50	NF	NF	NF	35	NF	NF	NF	2000	1000	500	290	5	2	500	3400	50	500
2	NF	75	100	67	NF	12.5	NF	NF	NF	NF	NF	NF	NF	NF	2500	500	1000	250	3	NF	550	3000	25	100
3	NF	NF	85	50	NF	7.5	25	14	NF	3	NF	NF	NF	NF	3000	750	750	200	NF	NF	450	1000	20	300
4	NF	90	65	75	75	NF	NF	NF	NF	NF	18	NF	NF	NF	3500	1000	300	180	NF	NF	100	2000	42	750
5	NF	60	50	25	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	400	750	750	160	NF	NF	200	2500	100	1650
6	17.5	25	65	NF	NF	NF	NF	NF	12.5	NF	NF	NF	NF	NF	3700	900	900	120	NF	NF	250	3300	500	2000
7	NF	80	NF	NF	50	NF	NF	NF	NF	NF	NF	NF	NF	NF	3150	900	750	90	3	NF	300	2000	1000	500
8	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	30	NF	NF	NF	2000	700	100	130	NF	NF	350	2300	300	750
9	NF	NF	NF	25	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	2500	850	650	250	NF	NF	400	2700	500	1000
10	7.5	NF	NF	15	NF	15	NF	3	NF	NF	NF	1.5	NF	NF	3000	700	900	250	9	NF	500	2000	750	1500
11	NF	NF	NF	25	30	NF	75	NF	NF	5	NF	NF	NF	NF	1000	500	750	280	NF	NF	500	1500	380	1000
12	NF	NF	NF	40	NF	NF	NF	NF	NF	NF	15	NF	NF	NF	1500	350	98	300	3	3	500	500	50	750
13	NF	40	NF	NF	40	NF	NF	NF	NF	NF	NF	NF	NF	NF	2000	400	50	300	NF	NF	450	75	65	1000
14	NF	NF	15	NF	30	NF	NF	NF	NF	NF	NF	NF	NF	NF	3000	500	25	260	NF	NF	295	850	25	500
15	17.5	NF	NF	NF	NF	NF	NF	4	8	NF	NF	NF	NF	NF	2500	300	40	270	2	NF	350	500	25	800
16	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	40	NF	NF	NF	1250	500	75	250	NF	NF	415	1400	16	1000
17	NF	30	NF	NF	NF	12.5	NF	NF	NF	NF	NF	NF	NF	NF	800	400	90	280	NF	NF	200	1900	25	100
18	NF	16	15	NF	50	NF	15	NF	NF	3	NF	NF	NF	NF	1500	750	300	250	NF	NF	300	1800	75	50
19	NF	25	NF	25	NF	NF	NF	NF	NF	NF	30	NF	NF	NF	2000	900	750	80	NF	NF	350	750	50	50
20	6	18	25	32	70	NF	NF	NF	NF	NF	NF	NF	NF	NF	2300	800	900	37.5	NF	2	50	NF	60	100

NF = Not found

TABLE - 35 Minor and trace elements in quartzites (altered) (ppm values)

Sample No.	Zr	Zn	As	Te	Cu	Th	Y	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti
1	46	100	750	45	2500	1000	3000	28.5	40	10	200	37.5	10	10	11000	3500	37.5	37.5	2600	180	37.5	NF	3700	4850
2	37	300	1000	85	1500	500	3500	10.0	NF	13	100	25	2.5	11	7500	300	12.5	12.5	2000	100	20	NF	3000	4000
3	21.5	550	500	70	2000	750	2000	25	50	18	250	12.5	5	11	5700	1000	30	65	2500	140	40	20	2000	3000
4	13	225	700	300	1000	900	950	18.5	NF	NF	250	50	2.5	12	5600	1400	10	180	2100	100	50	NF	1900	3500
5	25	50	900	87	750	500	1400	25	25	13	80	37.5	2.0	20	5500	2000	20	75	2450	95	12.5	9.5	500	4500
6	37.5	70	500	180	1500	750	2500	20	37.5	17	170	45	1.5	25	5000	2450	17.5	50	1700	95	20	15	300	5000
7	44.5	100	100	25	500	500	2000	28	19	5	290	NF	NF	30	4000	3000	45	55	2700	85	25	NF	750	4000
8	44	300	300	60	750	750	1000	20	NF	NF	230	NF	1.0	35	5200	2000	32.5	75.0	2000	170	11	30	2000	4500
9	43.9	180	300	75	500	950	3000	28	NF	18.5	290	NF	NF	40	4600	950	40	50	1000	190	NF	38	3000	5800
10	31	75	500	87	300	950	500	15	NF	NF	260	12.5	2	35	3000	1300	50	100	1500	170	NF	29	4000	5500
11	25	90	850	43	1000	500	250	12	25	NF	290	25	2.5	32.5	4200	850	75	75	2400	140	NF	20	3500	5000
12	37.5	300	1000	70	650	750	450	16	37.5	15	250	NF	NF	25	3400	1500	100	25	2700	180	NF	10	3500	4500
13	37.5	750	800	90	850	300	350	21	25	10	200	NF	1.5	27	5000	1000	37.5	150	2400	140	NF	28.5	360	5800
14	400	100	950	55	200	300	650	27	12.5	NF	170	12.5	NF	20	5600	700	50	50	1500	180	12.5	4.5	250	2000
15	31	620	750	75	756	500	100	20	22	NF	280	NF	2.5	23	> 5000	1700	25	25	2150	140	25	10	2000	1000
16	85	75	50	300	2000	750	250	15	NF	5	200	35	NF	26	8000	2500	12.5	90	1800	125	37.5	20	2500	500
17	17.5	100	100	50	2700	850	150	17	30	NF	290	NF	NF	30	3000	3000	25	38	2800	150	NF	NF	340 0	1500
18	25	300	500	25	3000	300	100	10	20	5	230	25	NF	35.5	5500	3500	10	5	3000	180	NF	NF	3200	3000
19	37.5	900	750	35	1000	500	100	15	NF	8	100	NF	NF	32	5000	2500	25	12.5	2000	170	NF	5	1000	4000
20	41.5	75	500	50	400	75	150	20	20	5	150	50	1.5	15	4000	1500	45	12.5	3000	80	NF	15	500	5000

NF = Not found

TABLE - 36 Minor and trace elements in quartzites (Unaltered) (ppm values)

Sample No.	Zr	Zn	As	Ta	Cu	Th	Y	La	Ge	Ga	Ce	Bi	Be	Ag	Al	Cr	Nb	Ni	Pb	Sn	V	Mo	Mn	Ti
1	10	25	50	35	50	NF	NF	5	5	NF	NF	NF	NF	NF	2500	500	3000	450	7.5	NF	880	2800	100	950
2	NF	NF	75	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	2100	400	1000	200	NF	7	800	2000	50	500
3	NF	35	35	NF	30	NF	NF	NF	NF	NF	NF	NF	NF	NF	2000	350	2000	300	NF	NF	800	1500	70	850
4	NF	NF	70	NF	NF	NF	NF	NF	NF	NF	25	NF	NF	NF	2400	500	2500	150	NF	NF	760	2500	520	900
5	NF	NF	55	NF	NF	NF	NF	NF	NF	3	NF	NF	NF	NF	2700	400	2900	250	NF	NF	750	2000	900	750
6	6	35	30	NF	40	NF	NF	16	NF	NF	NF	NF	NF	NF	2600	500	2300	350	NF	NF	750	1000	750	650
7	NF	15	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	1000	250	1500	400	3	NF	980	400	975	800
8	NF	15	NF	NF	NF	NF	NF	NF	NF	NF	12.5	NF	NF	NF	1800	400	2300	480	NF	3	920	300	550	500
9	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	1600	450	2600	450	NF	NF	880	250	950	750
10	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	2000	350	2900	430	NF	NF	960	500	500	950
11	NF	NF	NF	10	70	NF	NF	NF	NF	NF	35	NF	NF	NF	2500	300	1950	400	NF	NF	900	750	300	350
12	8	NF	NF	NF	NF	NF	NF	NF	10	2	NF	NF	NF	NF	3000	350	700	200	7	NF	950	1700	900	750
13	NF	NF	NF	NF	NF	NF	NF	3	NF	NF	NF	NF	NF	NF	3300	250	650	300	NF	NF	940	2700	750	900
14	NF	20	NF	NF	20	NF	NF	NF	NF	NF	NF	NF	NF	NF	3900	350	1450	260	NF	NF	800	2000	500	1000
15	NF	NF	40	NF	30	NF	NF	NF	NF	NF	NF	NF	NF	NF	3500	400	1600	350	NF	5	400	2400	900	1000
16	6	15	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	3300	500	200	440	4	NF	620	2000	500	750
17	NF	10	NF	NF	NF	NF	NF	NF	NF	3	NF	NF	NF	NF	3000	350	70	400	NF	3	720	1000	100	850
18	NF	NF	NF	NF	50	NF	NF	NF	NF	NF	NF	NF	NF	NF	2000	250	500	430	NF	NF	920	500	50	500
19	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	1100	350	1000	300	NF	NF	990	1500	300	250
20	10	NF	NF	15	30	NF	NF	4	7	NF	25	NF	NF	NF	800	450	1500	300	NF	NF	140	2600	750	400

NF = Not found

Table 37 - Chemical changes produced by alteration in phyllites at Sikhip copper deposits (wt. percent).

Constituents	Unaltered phyllites 30 ft. from ore zone	Altered phyllites 20 ft. from ore zone	Altered phyllites 10 ft. from ore zone	Altered phyllites adjoining ore zone	Ore zone
SiO_2	40.20	52.50	50.99	50.10	52.35
Al_2O_2	26.20	20.10	20.40	15.45	27.12
Fe_2O_3	5.10	5.50	4.01	5.10	6.14
FeO	6.30	6.50	5.00	6.25	7.40
CaO	3.80	1.80	1.80	1.55	1.20
MgO	2.20	2.30	3.18	3.35	3.85
Na_2O	5.80	2.50	2.08	1.85	1.20
K_2O	3.30	3.80	3.35	3.85	4.10
H_2O^+	1.40	1.60	2.75	3.20	4.40
H_2O^-	0.25	0.50	1.85	2.45	3.25
TiO_2	2.20	1.20	1.10	1.09	1.10
P_2O_5	2.08	1.01	0.15	0.08	0.03
MnO	NF	NF	0.78	1.25	2.01
CO_2	NF	NF	1.32	2.31	3.21
FeS_2	NF	NF	1.20	1.25	2.00
TOTAL	99.04	99.31	99.96	99.13	99.36
SiO_2/MgO	18.27	22.84	16.03	14.11	13.59
FeO/MgO	2.863	2.826	1.575	1.76	1.922
CaO/Na_2O	0.655	0.720	0.865	0.837	1.000
CaO/Na_2O+K_2O	0.417	0.285	0.331	0.271	0.226
Na_2O/K_2O	1.757	0.657	0.628	0.480	0.292

NF = Not found

TABLE - 38 Chemical changes produced by alteration in schists at Rangpo copper deposits (wt per cent)

Constituents	Unaltered schists 25 ft from ore zone	Altered schists 20 ft from ore zone	Altered schists 15 ft from ore zone	Altered schists 10 ft from ore zone	Altered schists adjoining ore zone	Ore zone
SiO_2	44.72	49.72	52.29	54.68	54.20	55.00
Al_2O_3	24.40	22.10	22.38	15.42	9.21	2.10
Fe_2O_3	3.04	2.84	2.08	2.60	4.10	5.20
FeO	4.00	3.24	2.60	3.68	6.02	6.00
CaO	2.58	2.76	1.34	1.78	0.21	0.42
MgO	1.62	2.52	1.54	1.31	4.22	6.02
Na_2O	3.78	1.18	0.54	0.41	0.12	0.01
K_2O	5.44	3.48	4.15	6.78	6.43	6.50
H_2O^+	5.43	6.52	5.70	4.73	6.96	7.00
H_2O^-	0.19	0.09	1.95	2.86	2.11	4.00
TiO_2	2.81	0.68	0.66	0.39	0.22	0.01
P_2O_5	1.13	0.24	0.17	0.10	0.01	0.02
MnO	0.03	0.03	0.03	0.06	1.01	2.00
CO_2	0.01	2.74	2.95	2.10	2.21	3.38
FeS_2	NF	NF	1.42	2.35	3.13	0.80
S	NF	NF	NF	NF	0.10	0.50
TOTAL	99.18	99.04	99.79	99.20	99.16	99.85
SiO_2/MgO	27.60	19.73	34.40	41.74	12.84	9.13
FeO/MgO	2.96	1.28	1.68	2.80	1.42	0.99
CaO/Na_2O	0.682	2.33	2.48	4.34	1.75	0.42
$CaO/Na_2O + K_2O$	0.279	0.592	0.285	0.247	0.032	0.064
Na_2O/K_2O	0.694	0.339	0.130	0.060	0.018	0.001

NF = Not found

TABLE - 39 Chemical changes produced by alteration in slates at Peku copper deposits

(wt. per cent)

Constituents	Unaltered slates 25 ft from ore zone	Altered slates 15 ft from ore zone	Altered slates 10 ft from ore zone	Altered slates 5 ft from ore zone	Altered slates adjoining ore zone	Ore zone
SiO_2	38.60	57.35	52.48	51.60	50.00	41.00
Al_2O_3	28.65	16.30	16.44	15.08	6.10	2.00
Fe_2O_3	3.12	2.12	3.80	3.50	5.60	10.00
FeO	3.20	3.38	4.80	4.95	5.80	6.00
CaO	8.55	5.66	4.95	2.25	0.12	0.10
MgO	3.20	2.41	5.21	5.10	6.10	7.00
Na_2O	6.36	4.50	2.45	1.33	0.10	0.08
K_2O	1.69	3.39	2.30	3.18	3.00	4.00
H_2O^+	0.41	1.70	3.60	4.32	6.10	8.12
H_2O^-	0.31	1.75	1.80	2.00	2.01	6.31
TiO_2	3.00	1.08	1.07	0.08	0.01	0.01
P_2O_5	2.92	0.10	0.06	0.02	NF	NF
MnO	0.10	0.12	0.92	2.00	1.10	3.00
CO_2	0.08	0.02	0.06	2.35	4.00	6.00
FeS_2	NF	NF	NF	2.00	4.10	5.15
S	NF	NF	NF	0.08	0.29	0.30
TOTAL	99.19	99.88	99.96	99.84	99.43	99.07
SiO_2/MgO	12.06	23.79	10.06	10.11	8.19	5.85
FeO/MgO	1.00	1.402	0.921	0.97	0.95	0.857
CaO/Na_2O	1.344	1.257	2.020	1.691	1.20	1.25
$CaO/Na_2O + K_2O$	1.062	0.717	1.041	0.498	0.038	0.024
Na_2O/K_2O	3.763	1.327	1.065	0.418	0.033	0.02

NF = Not found

TABLE - 40 Chemical changes produced by alteration in quartzites at Kalimpong copper deposits.

(wt. per cent)

Constituents	Unaltered quartzites 20 ft from ore zone	Altered quartzites 10 ft from ore zone	Altered quartzites 5ft from ore zone	Altered quartzites adjoining ore zone	Ore zone
SiO_2	60.80	66.34	77.95	74.41	62.35
Al_2O_3	24.60	25.12	12.71	11.03	1.01
Fe_2O_3	0.30	0.24	0.29	0.18	5.59
FeO	1.04	2.12	1.75	3.31	4.21
CaO	4.20	2.25	1.10	0.29	0.02
MgO	0.050	0.10	0.21	0.39	2.45
Na_2O	3.30	0.35	0.12	0.02	0.01
K_2O	0.24	0.18	0.34	0.41	1.00
H_2O^+	0.41	0.94	1.12	2.52	6.60
H_2O^-	0.20	0.35	0.83	1.61	3.45
TiO_2	2.25	0.20	0.19	0.16	0.10
P_2O_5	2.15	0.11	0.08	0.02	0.05
MnO	0.10	0.49	0.95	1.78	2.05
CO_2	0.20	0.87	1.73	3.51	3.60
FeS_2	NF	NF	0.14	0.58	2.10
S	NF	NF	0.10	0.20	0.20
TOTAL	99.79	99.46	99.61	98.05	
SiO_2/MgO	1216.00	663.40	371.1	190.79	25.448
FeO/MgO	20.8	21.20	8.332	8.487	1.7
CaO/Na_2O	1.272	6.428	9.166	14.50	2.00
$CaO/Na_2O + K_2O$	1.196	4.245	2.4	0.67	0.019
Na_2O/H_2O	13.75	2.0	0.353	0.0487	0.01

NF = Not found

TABLE - 41 Chemical analysis of chlorites from Sikhip copper deposits. (wt. per cent)

Constituents	Chlorite derived away from the mineralized zone in the unaltered country rocks (average of 5 analyses).	Chlorite derived from the altered wall-rocks and associated with chalcopyrite in the ore zone (average of 10 analyses).
SiO_2	33.84	23.60
TiO_2	1.41	0.02
Al_2O_3	26.95	11.90
Fe_2O_3	0.00	1.02
FeO	15.40	36.95
MnO	0.13	2.60
MgO	2.31	11.06
CaO	8.68	0.10
Na_2O	6.10	0.01
K_2O	0.02	0.28
H_2O^+	4.00	12.17
H_2O^-	0.04	0.26
TOTAL	99.68	99.97
OXIDE RATIOS IN CHLORITE		
SiO_2/MgO	14.64	2.133
FeO/MgO	6.60	3.44
CaO/Na_2O	1.42	10.00
$CaO/Na_2O + K_2O$	1.41	0.343
Na_2O/K_2O	3.05	0.035

TABLE - 42 Average chemical analyses of biotites (Wt. per cent).

Constituents	Biotite derived from the wall-rocks and associated with sulphide ore minerals from Peku copper deposits. (average of 6 analyses)	Biotite derived away from the mineralised zone in the unaltered country rocks from Peku copper deposits. (average of 4 analyses)	Biotite derived from the Tourmaline Granite (younger granitic rocks) occurrring in the northern areas (average of 10 analyses)	Biotite derived from Granite-Gneiss occurring in the southern areas (average of 8 analyses)
SiO_2	37.15	38.40	38.70	37.33
TiO_2	2.12	1.52	3.04	1.74
Al_2O_3	13.84	20.55	16.45	20.30
Fe_2O_3	3.71	9.69	4.03	2.79
FeO	18.40	6.95	16.31	12.30
MnO	1.01	0.34	0.08	0.06
MgO	8.95	7.48	7.91	13.23
CaO	2.04	2.59	0.17	0.08
Na_2O	1.86	2.69	0.04	1.30
K_2O	9.17	6.16	8.30	7.75
F	0.32	N.F.	1.37	0.04
H_2O^+	1.34	2.95	2.62	2.81
H_2O^-	0.08	0.63	0.95	0.22
TOTAL	99.99	99.95	99.97	99.96
		OXIDE RATIOS IN BIOTITE		
SiO_2/MgO	4.15	5.13	4.89	2.82
FeO/Na_2O	9.89	2.58	407.75	9.46
$CaO/Na_2O + K_2O$	0.184	0.292	0.0203	0.0088
Na_2O/K_2O	0.202	0.436	0.0048	0.16
$FeO/Fe_2O_3 + TiO_2$	3.17	0.619	2.32	2.67

NF = Not found

TABLE 43 - Minor and trace elements in limonite from copper and lead-zinc deposits (ppm values).

S.No.	Location	Fe	Mn	Si	B	Al	Ti	Ca	Cr	Mg	Sr	Ba	Zn	Cd	Cu	Pb	Sn	Ag	As	Sb	Se	Ni	Co	Zr
1	Kalimpong area	>10000	>1000	>1000	NF	>1000	NF	>500	NF	>500	110	110	>5000	>500	3500	>5000	NF	<150	1500	>500	NF	>500	>100	NF
2	Sikhip area	>10000	>1000	>1000	150	>3000	>3000	800	150	>3000	<100	400	>500	300	>5000	800	200	150	1000	400	700	300	NF	NF
3	Rishi area	>10000	>4000	>10000	150	1000	>1000	>2000	NF	600	NF	600	2500	200	1500	3000	NF	300	800	200	NF	NF	>100	300
4	Rishi area	>10000	>5000	>3000	60	>2000	>1000	>3000	100	>4000	NF	300	>1000	500	>5000	>1000	100	240	300	100	50	NF	NF	200
5	Rishi area	>10000	>3000	1500	NF	>1000	1200	500	400	600	<100	300	>2000	300	>1000	>3000	200	500	1000	150	<100	NF	NF	NF
6	Rangpo area	>10000	>5000	1000	NF	1000	600	>4000	NF	1000	NF	<20	800	NF	>1000	1000	NF	<2	1000	200	NF	NF	NF	NF
7	Pachikheni area	>10000	>3000	>1000	NF	1500	450	>2000	NF	1000	150	NF	100	NF	800	100	NF	<2	100	10	NF	NF	NF	NF
8	Peku area	>10000	>5000	>2000	NF	2000	550	>10000	NF	>1000	100	NF	80	NF	50	100	NF	<1	200	5	100	NF	NF	NF
9	Sikhip area	>10000	>2000	>3000	NF	>2000	1000	800	50	500	30	200	50	NF	750	>50	NF	<1	100	<1	50	NF	NF	NF

NF = Not found

TABLE - 44 Minor and trace elements in malachite from copper and lead-zinc deposits (ppm values)

S.No.	Locality	Cu	Fe	Zn	Cd	Pb	Ag	Sb	Sn	Mn	Ni	Ti	Mg	Be	Si	Al
1	Rishi area	>10000	>1000	1000	NF	>1000	50	100?	NF	1000	300	100	100	50	>1000	>2000
2	Sikhip area	>10000	>5000	>1000	NF	>1000	100	100	NF	>1000	50	50	80	20	>2000	>2000
3	Peku area	>10000	>5000	>1000	NF	800	200	100	50	>1000	20	40	60	10	>1000	>1000

NF = Not found

TABLE - 45 Minor and trace elements of cerussite, pyromorphite and rozenite (ppm values)

S.No.	Locality and name of mineral	Pb	Zn	Cu	Ag	Cd	Fe	Mn	Ba	Sr	Ca	Mg	Sb	As	Bi	Sn	Ni	Co	Cr	Al	Ti	B	Si	P	Mo	V	La	Y	Yb
1	Rishi area / CERUSSITE	>10000	500	400	20	2	500	65	45	<1	<10	50	NF	NF	NF	1	NF	NF	NF	800	NF	NF	500	NF	NF	NF	NF	NF	NF
2	Rishi area / PYROMORPHITE	>10000	NF	80	850	NF	>1000	>1000	500	NF	700	600	400	500	<1	NF	NF	NF	>700	>4000	>1000	<1000	>1000	>1000	1000	80	NF	100	90
3	Rishi area / ROZENITE	500>2000		75	NF	NF	>1000	>10000	NF	NF	800>2000		6	200	NF	NF	80	100	NF	600	NF	NF	1000	NF	NF	NF	NF	NF	NF

NF = Not found

TABLE - 46 Minor and trace element content of galena from lead-zinc deposits (ppm values)

S.No.	Locality	Ag	Sn	Cu	Zn	Cd	As	Sb	Bi	Mn	Fe	Tl	Ni	In	Pb	Ba	V	MO	CO
1	Rishi area	10	8	20	225	100	25	NF	4	285	50	130	50	NF	10000	10	15	3	3
2	Rishi area	NF	3	18	150	300	14	3	9	25	20	120	10	NF	10000	15	5	2	NF
3	Rishi area	8	7	10	90	30	60	NF	8	15	100	10	5	4	10000	18	8	5	NF
4	Rishi area	3	10	15	100	20	50	10	5	250	200	100	25	NF	10000	5	10	2	5
5	Rishi area	NF	8	20	200	10	50	5	7	25	15	50	12	NF	10000	10	2	5	2

NF = Not found

TABLE -47 Minor and trace elements in pyrites and marcasite from copper and lead-zinc deposits (ppm values)

Name of mineral	Location	Si	Al	Ti	Mn	Co	Ni	Cd	Ag	Sb	As	Cr	Cu	Mo	Pb	Sr	V	Zn	Sn	Bi
Pyrite	Rishi	1000	700	500	50	20	5	15	6	30	2400	20	5	20	14	70	60	8	10	5
	Rishi	400	600	400	80	10	5	10	10	100	1350	30	5	50	15	80	50	10	10	10
	Rishi	500	800	150	100	40	8	40	5	5	1500	10	10	100	5	20	30	10	10	5
	Rishi	300	400	80	40	40	5	50	4	8	10000	10	10	40	10	10	60	5	10	8
	Rishi	800	100	120	60	30	6	25	5	6	2350	10	5	60	15	40	65	10	10	2
	Rishi	700	200	100	90	30	5	15	10	8	2200	20	10	80	8	90	50	15	5	5
	Kalimpong	500	400	100	500	35	10	150	10	10	500	30	10	50	10	40	10	8	10	3
	Kalimpong	400	300	50	50	40	20	10	10	10	500	20	10	30	5	80	25	3	10	5
	Kalimpong	300	100	50	200	25	5	15	10	50	4800	10	10	30	5	80	20	NF	10	2
	Kalimpong	500	100	60	20	30	5	20	10	50	8000	10	10	50	15	90	30	10	NF	5
	Kalimpong	500	1400	30	10	35	5	30	10	5	1200	30	10	20	20	50	30	15	5	5
	Sikhip	1000	200	100	60	100	60	20	15	50	1000	20	8	40	4	80	30	10	10	5
	Sikhip	1000	250	50	50	60	35	15	8	10	600	25	10	30	5	70	10	5	10	5
	Peku	1500	750	500	150	300	100	45	15	10	5000	30	10	60	5	100	60	2	10	15
	Peku	1050	950	300	100	300	25	15	20	100	2000	30	15	100	10	80	80	5	8	15
	Pachikhani	1000	300	100	100	100	50	25	10	50	1500	10	15	50	10	80	25	NF	10	10
	Pachikhani	1100	1000	100	20	100	45	40	15	5	2800	10	10	30	12	40	10	5	10	10
	Rothakhani	100	100	30	35	65	20	25	10	20	2150	10	5	10	7	10	15	4	10	2
	Rothakhani	80	200	40	60	60	15	50	5	10	4000	20	10	10	8	20	40	2	10	3
	Bhotang	1000	800	100	100	100	50	35	8	16	1500	45	10	60	20	80	60	10	10	25
	Bhotang	1100	1000	200	80	200	90	25	15	6	1700	50	15	35	25	80	20	15	8	20
	Tukhani	500	400	20	60	20	15	35	10	8	2100	10	10	50	5	20	20	NF	6	5
	Tukhani	100	100	100	80	20	10	10	10	30	10000	20	10	50	5	10	30	NF	10	NF
Marcasite	Rishi	200	300	100	50	20	5	15	3	8	30	29	4	50	10	50	25	5	3	3
	Pachikhani	250	400	100	50	100	10	25	3	5	25	15	2	40	5	30	35	2	4	5

NF = Not found

TABLE - 48 Minor and trace elements in anglesite from lead-zinc deposits (ppm values

S.No.	Locality	Pb	Fe	Mn	Cu	Mg	Ba	Sr	Al	Si	Zn	Cd	Cu	Ag	Sn	Bi	As	Sb
1	Rishi area	10000	4000	90	2000	100	50	150	1000	1000	400	50	150	180	60	90	100	100
2	Rishi area		1000	800	3000	80	60	100	500	2000	800	20	35	80	100	80	500	200

TABLE - 49 Minor and trace element content in sphalerite from lead-zinc deposits (ppm values)

S.No.	Locality	Zn	Cd	Fe	Mn	Ag	Cu	Pb	Sn	In	As	Sb	Si	Al	Ti	Ni	Co	Ce	Ba	V	Mo	Ga
1	Rishi area	>10000	4200	>10000	800	NF	20	100	8	9	15	80	400	800	NF	30	4	8	8	2	NF	3
2	Rishi area	>10000	3300	>10000	600	4	8	80	6	NF	9	5	900	90	90	55	5	4	NF	6	NF	9
3	Rishi area	>10000	5100	>10000	1500	10	25	1000	9	8	4	60	20	30	NF	8	8	30	25	4	2	NF
4	Rishi area	>10000	>1000	>10000	3000	10	30	50	25	9	20	30	50	8	40	15	3	40	35	2	NF	NF
5	Rishi area	>10000	>10000	>10000	5300	4	12	40	NF	4	5	9	100	10	10	10	2	25	60	10	3	4

NF = Not found

TABLE:50 Minor and trace element contents in chalcopyrite from copper deposits (ppm values)

S.No.	Locality	Fe	As	Sb	Pb	Cu	Zn	Cd	Ag	Sn	Co	Ni	Al	Si	Mn	Bi	V	MO	Ti
1	Sikhip area	>10000	100	15	50	>10000	40	10	5	5	100	200	500	600	100	15	70	40	110
2	Kalimpong area	>10000	80	10	350	>10000	25	5	3	5	90	100	400	500	90	10	60	30	90
3	Peku area	>10000	130	20	500	>10000	300	10	6	10	160	350	1000	1200	100	25	120	80	140
4	Rangpo area	>10000	150	25	1100	>10000	500	10	8	10	210	500	1100	1250	120	50	150	100	160
5	Pachikhani area	>10000	100	10	100	>10000	50	5	5	8	70	400	600	700	100	20	110	70	100

TABLE - 51 Minor and trace element contents in pyrrhotite from copper deposits (ppm values)

S.No.	Locality	Fe	Cu	As	Sb	Pb	Zn	Cd	Ag	Sn	CO	Ni	Al	Si	Mn	MO	V	Bi	Ti
1	Peku area	>10000	>10000	80	70	100	40	6	6	8	110	215	300	410	90	25	30	8	100
2	Rangpo area	>10000	>10000	80	80	210	100	8	8	10	125	275	400	600	100	30	45	10	130